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ONSE OF BRIDGE STRUCTURAL MEMBERS UNDER WIND-INDUCED VIBRATIONS

June 1976
Final Report

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Washington, D. C. 20590

FOREWORD

This report presents the results of a comprehensive investigation into the structural dynamics of long, slender members of contemporary cross-section shapes. It will be primarily of interest to those researchers concerned with wind resistant highway structures.

Results of this study are being integrated into Federally Coordinated Project 5A entitled "Improved Protection Against Natural Hazards of Earthquake and Wind."

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Charles F. Scheffey
Director, Office of Research

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16. Abstract

Structural dynamics of long slender member of contemporary cross-section shapes are investigated in a comprehensive manner for the purpose of precluding vortex excited vibration and mitigating damages to the member due to fatigue. The unique features are (1) the ends can have various degree of elastic restraint,(2) different levels of axial tension are allowed for both flexural and torsional vibrations, (3) flow regime can be either subcritical (single-frequency resonance) or supercritical (random shedding). The text consists of recommended design guide with design charts appended with supplements which show the basis of the design guide, mathematical theories, illustrative examples and a lengthy bibliography.

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Appreciation is also given to Mr. Bernard G. Dennis, Jr., who performed much of the computer work, and prepared all of the numerical examples and illustrations; and to Lotta Chi, who patiently organized all reference materials in detailed subdivisions and categories for easy access by the technical personnel, and then compiled them into a very comprehensive bibliography.

FOREWORD

This research deals with the mechanism, properties and characteristics of vortex shedding vibrations of bridge members for the purpose of disseminating the researched information into a design aid in order to mitigate the damages done to long, slender members through fatigue caused by wind-induced vibrations.

The main results of this investigation are reduced into twelve sections, which are listed as the texts of this report; complicated formulas that require more than ordinary calculation efforts are presented in graph form in Appendix A. The text and Appendix are integral parts of a proposed design guide. Together, they can be used, on our opinion, by structural designers in a routine manner.

To provide adequate background of this design aid four supplements are appended with the text. These supplements should be consulted by those who wish to understand the basis upon which the design aid has been developed.

Supplement Part A is a digest of literature which was reviewed during the course of this investigation. It provides comprehensive background material on the historical development, origin and behavior of vortex-shedding mechanism. These form a basis for establishing the methods and devices to suppress the

formation of the vortex street and thus reduced the severity of vibration of the structural members. The available Strouhal numbers of the most commonly known cross-shapes of structural applicability are listed as are other useful engineering data including damping, lift and end-fixity coefficients.

Supplement Parts B and C consist of all mathematical theories and implementation of these theories. For the convenience of the users, we have segregated the mathematical and computational aspects from each other.

The mathematical theory of free vibration including the frequency equations and mode shapes are given in Chapter I, Part B. The flexural vibration theory is applicable to a beam with elastic constrained ends and with axial tension. This is believed to be the most general formulation in the framework of Euler-Bernoulli theory. The torsional vibration theory is applicable to thin closed and open sections with consideration to warping and axial tension. Neither theory has appeared in the literature in this generality and this is believed to have advanced the state of the art. The detailed evaluation of natural frequencies of various types of vibration is given in Part B, Chapter I. All results are given in graph form, in Appendix A of the main text and also in Part E.

Numerical examples which demonstrate how the theory and natural frequency graphs can be used to determine the corresponding wind velocities which cause resonance in the bridge members are given in Part C, Chapter I. The mode shapes of a vibrating beam are used for random vibration as described later in the text.

The mathematical theory which determines the amplitude of vibration of a rigid beam in single frequency resonance (subcritical flow) is given in Part B, Chapter II. The forcing function was assumed to be a van der Pol oscillator, used by Hartlen and Currie for a circular cylindrical bar. In the present work, we adapted it to an H-section and calibrated the formulation to the experimental results by Narita. The implementation of this theory to an elastic beam is given in Part C, Chapter II, accompanied by a numerical example.

The response of a beam to random vibrations is derived in Part B, Chapter III, in a self-content manner. The theory is implemented to a beam with constrained ends. The implementation of this theory is given in Part C, Chapter III. The mean deformation and the mean squared deformation are obtained from the formulations given in Part B, Chapter I. The recommended lift coefficients are suitable for H-beams and box beams. It was shown that in most cases the one term solution will give better than 95% accuracy. Since the first mode of vibration is

consistent in sign, the rms deflection is the same as the mean deflection. For this reason, the flexural stress as shown in Part C, Chapter II, can be determined by a simpler procedure than the conventional double differentiation method which is quite complicated in computation.

Supplement Part D consists of a comprehensive bibliography of nearly 900 entries, accompanied by a summary of search procedure and leading articles. Supplement Part E consists of a complete set of graphs for natural frequency determination especially for unsymmetrical cases, i.e., beams having unequal end-fixities.

RECOMMENDATIONS FOR THE ANALYSIS OF BRIDGE MEMBERS AGAINST WIND INDUCTED VIBRATIONS

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3. Assumptions
4. Strouhal Numbers
5. Damping
6. Lift Coefficient
7. End Fixity Condition of a Member
8. Natural Frequency
9. Nominal Wind Velocity at Resonance
10. Deflection of Member in Subcritical Flow Condition
11. Deflection of Member in Supercritical Flow Condition
12. Bending Stress of Member Undergoing Known Deflection

1. Notations

A = Cross-sectional area

B_n = Amplitude of nth cycle of vibration

C_L = Lift Coefficient

E = Young's modulus of elasticity of steel

$= 29 \times 10^6$ psi

I = Area moment of inertia of member under consideration

I_i = Area moment of inertia of lateral members in same joint

L = Length of member under consideration

L_i = Length of member in same joint

R_e = Reynolds number

S_f = Power spectrum function

St = Strouhal number

V = Wind velocity

a = Moment coefficient = M/qL^2

b = Deflection coefficient = $w_{max}EI/qL^4$

c = Extreme fiber distance

d = Depth of member in direction perpendicular to wind direction

e = Naperian base of logarithm

f_i = ith natural frequency

f = Frequency in Hertz

f_b = Flexural (bending) stress

h = width of member

ρ_a = mass density of air

ρ_m = mass density of member

q = Uniformly distributed transverse load

w = Deflection

w_{max} = Maxumum deflection (amplitude)

$\bar{w}$ = Mean deflection assumed to be $\frac{1}{2} w_{max}$

γ = Structural damping coefficient

$= \delta/2\pi$

δ = Logarithmic decrement

σ = End-fixity condition

ω = Circular natural frequency

2. Scope

This chapter covers the design of slender bridge members subject to wind-induced vibrations characterized by excursions in the direction perpendicular to the wind direction. The vibrations considered herein are caused by vortex-shedding in both periodical (sub-critical) and random (super-critical) ranges of Reynolds numbers. Vibrations due to flutter, buffeting, and galloping are beyond the scope of this chapter. The structural members are restricted to those of which the cross section has at least two axes of symmetry, e.g., circular, rectangular, box, H-sections, double-channel sections, etc. These type of sections are commonly used as tension members in the modern bridges. Compression members employing built-up sections usually have only one axis of symmetry and are capable of coupled torsional and flexural vibrational nodes. A comprehensive analysis

must be conducted specifically for such cases.

3. Assumptions

(a) The assumptions made in a general "strength of material" analysis of a member subjected bending and torsional conditions shall apply to the member being analyzed.

(b) Wind forces are assumed to be acting in the lateral direction of the member and perpendicular to the principal axes of the member.

(c) Members are assumed to be spaced such that there is sufficient room for the wake to fully develop without interference from any adjacent members, behind the member being analyzed.

(d) It is assumed that: (1) The natural frequencies of the member being analyzed are widely separated from one another, (2) The damping is small, and (3) The lift forces are spatially independent.

4. Strouhal Numbers

For design purpose, the Strouhal numbers for common cross-sections shall be:

Circle	Rectangle	H-Section
0.20	$0.13(\frac{h}{d}<1.0)$	0.12

5. Damping

Damping coefficient shall be expressed in terms of the logarithmic decrement, which is defined to be the natural logarithm of the ratio of two successive peak amplitudes in a free, decreasing oscillation, i.e., if B_n and B_{n+1} are the nth and (n+1)th amplitudes, respectively, the

$$\delta = \text{Log}_e \frac{B_n}{B_{n+1}}.$$

For design purposes, δ may be taken as 0.02 for members capable of resisting flexural moments, or 0.08 for flexible members including steel wire ropes. Structural damping may be taken to be $\gamma = \delta/2\pi$

6. Lift Coefficient

The fluctuating or time-dependent lift coefficient is dependent on the Reynolds number and surface characteristics of the member. For accurate analysis the lift coefficient should be determined by wind tunnel tests. For design purposes, 0.6 and 1.2 may be used as the r.m.s. and peak values of lift coefficients, respectively.

7. End-Fixity Condition of a Member

The end fixity condition of a long slender member in a truss or a frame is given by

$$\sigma = \frac{4}{n} \frac{\sum_i I_i/L_i}{I/L}$$

Where $\sum_i I_i/L_i$ = Sum of stiffness of all the lateral members in a joint other than member under consideration

I/L = Stiffness of the member under consideration

n = A constant indicating the continuity condition at the joint, i.e., n = 1 for members which terminate themselves at the joint, such as a hanger; n = 2 for members which are continuous through the joint such as the lower chord of a truss.

8. Natural Frequency

The natural frequencies of a bridge member is affected by the section properties, axial tensile force* and the end-fixity of the member. The end-fixity of a member shall be determined by the method as described in Section 7 of these recommendations. The recommended prevailing tensile force in the member shall be that caused by combination of dead load and one fourth of the design live load. The natural frequency coefficients for the first three flexural and torsional modes may be obtained from Figs. 1 through 10, for all cases except for thin closed sections. In the latter case, natural frequency coefficients shall be obtained from Table 1.

9. Nominal Wind Velocity at Resonance

The nominal wind velocity which causes resonance in a bridge member shall be determined by

*The figures should be used for tensile members only. The general method is applicable to compression members for which the natural frequencies are lower.

$$v = \frac{fd}{St}$$

This velocity shall be used to compute the Reynolds numbers associated with the flow. Reynolds number may be computed by

$$R_e = 780\ Vd$$

if V is in MPH and
d in inches.

The Reynolds number will indicate the flow regime for circular members. If the Reynolds number is below 1.0×10^5, the flow is in the Strouhal range. If the Reynolds number is within 1.0×10^5 to 4.0×10^5 the flow is in the transition range depending on upstream turbulence. If the Reynolds number is above 4.0×10^5, the flow is in the super-critical range and random shedding takes place. This information shall be used to determine which of the two approaches described in the next two sections shall be used to calculate the deflection in the member. For structural shapes, subcritical flow prevails for all Reynolds numbers.

10. Deflection in Subcritical Flow

The deflection of the bridge member in subcritical flow shall be analyzed by Fig. 11 which shows a relation between the non-dimensional amplitude $\bar{w}/d$ and a non-dimension damping $\frac{\gamma A \rho_m}{\rho_a d^2}$. Thus, the mean deflection $\bar{w}$ can be determined from known area, depth and structural damping coefficient. The corresponding flexural stress can be computed by a method suggested in section 12.

11. Deflection of Member in Supercritical Flow (Random Shedding) Condition

The mean deflection $\bar{w}$ of a bridge member undergoing a random vibration shall be determined by

$$\frac{\bar{w}}{d} = 3.1 \times 10^{-6} C_L \frac{V^2}{A(f_1)^2} \sqrt{\frac{S_f (St_1) St_1 \pi}{\delta}}$$

Where S_f (St) is the normalized power spectrum. Power spectra for cylindrical, square and H-sections are given in Figs.12, 13A and 13B, respectively. The formula is valid provided that f_1/f_3 is less than 0.2. The corresponding flexural stress can be determined by a method suggested in the next section.

12. Bending Stress in Member Undergoing a Known Deflection

The flexural stress caused by wind induced vibrational deformation shall be calculated by:

$$f_b = \frac{a}{b} E \frac{\bar{w}}{d} \left(\frac{d}{L}\right)^2$$

where a/b is given by Fig. 14, corresponding to a known end fixity condition σ, as determined in Section 7.

This bending stress shall be added to the stresses imposed on the member by the normal dead and 25 percent of live load combination. If the total computed stress exceeds the endurance limit of the structural material, the designer should employ a suitable measure to obviate this condition.

APPENDIX A

The following notations are given for Figs 1-10.

For bending vibrations (open and closed sections):

$$P = \frac{TL^2}{EI}$$

where T = Axial tensile force in the member

L = Span length

E = Young's modulus of elasticity

I = Moment of inertia (transverse to wind direction)

$$Q = \frac{\rho_m A \omega_n^2 L^4}{EI}$$

where ρ_m = Mass density of member

A = Cross-sectional area of member

ω_n = n^{th} circular natural frequency

For torsional vibration (thin open sections):

$$P = \frac{(GC + \frac{T}{A} I_p)L^2}{EC_w}$$

$$Q = \frac{\rho_m I_p \omega_n^2 L^4}{E C_w}$$

where G = Modulus of elasticity for shear

C = Torsional constant

I_p = Polar moment of inertia

C_w = Warping constant

For torsion of thin closed sections, see Table 1.

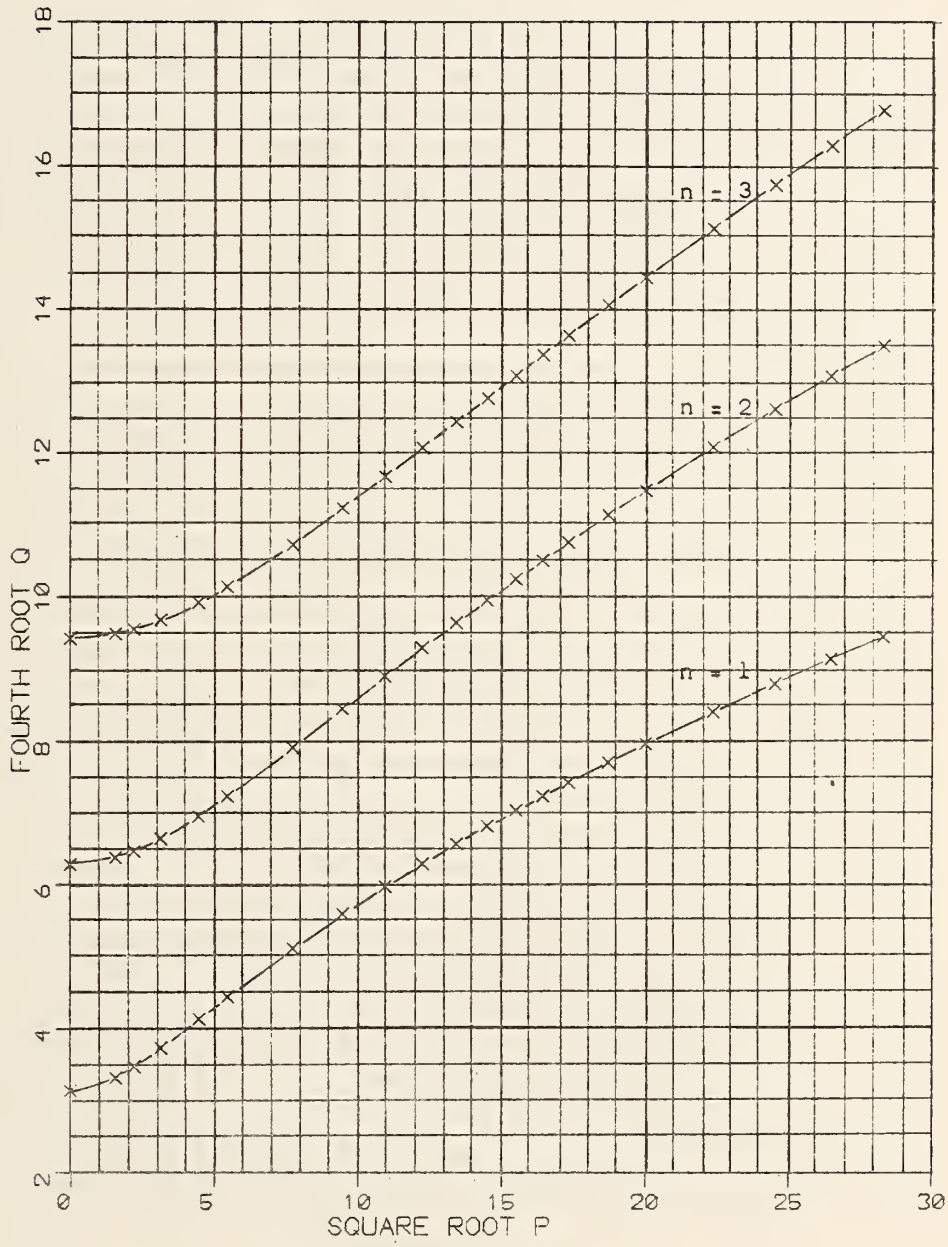


FIG. 1 NATURAL FREQUENCY AT DIFFERENT TENSION
SYMMETRICAL BEAM WITH HINGED ENDS (σ=0)

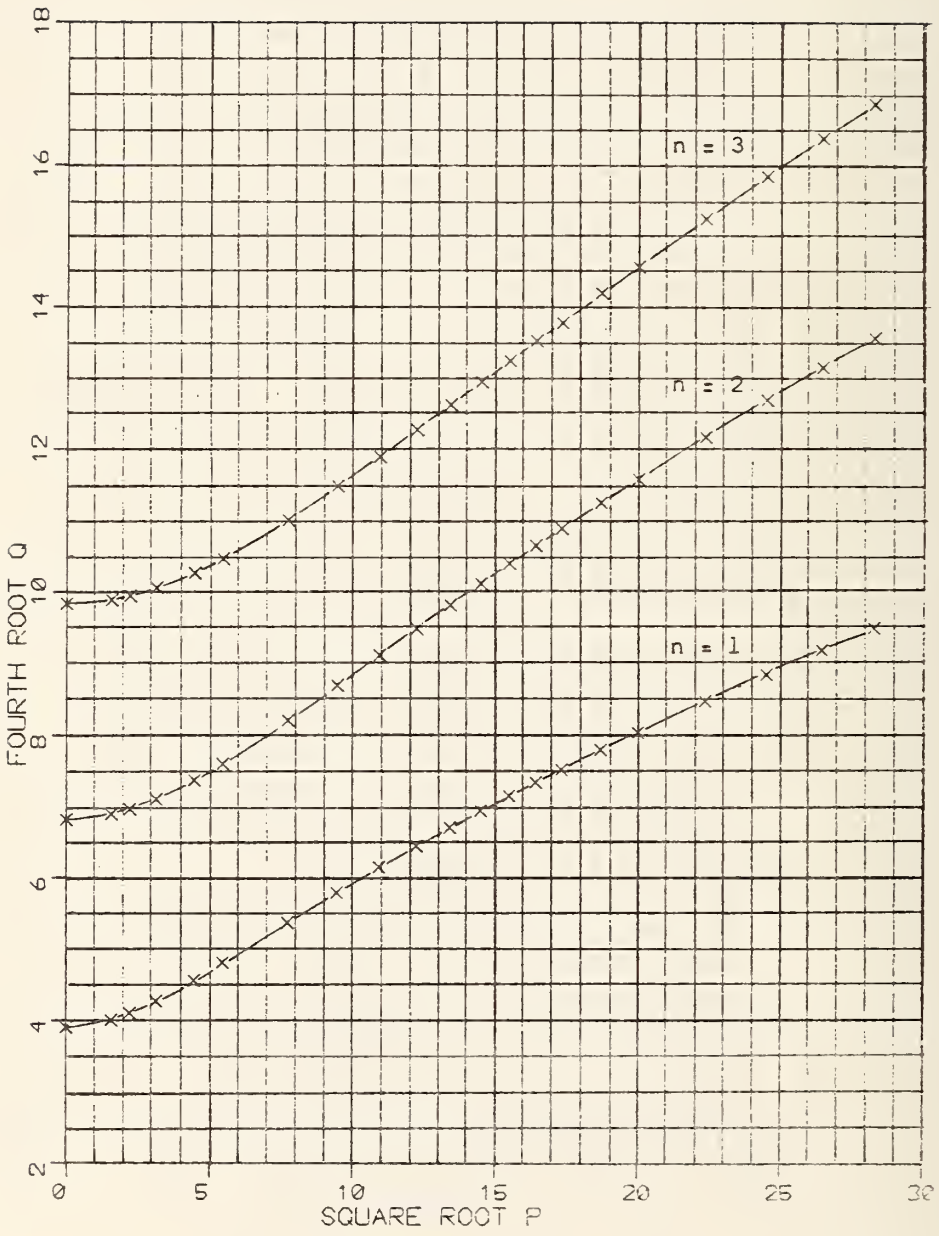


FIG. 2 NATURAL FREQUENCY AT DIFFERENT TENSION
SYMMETRICAL BEAM WITH $\sigma=5$

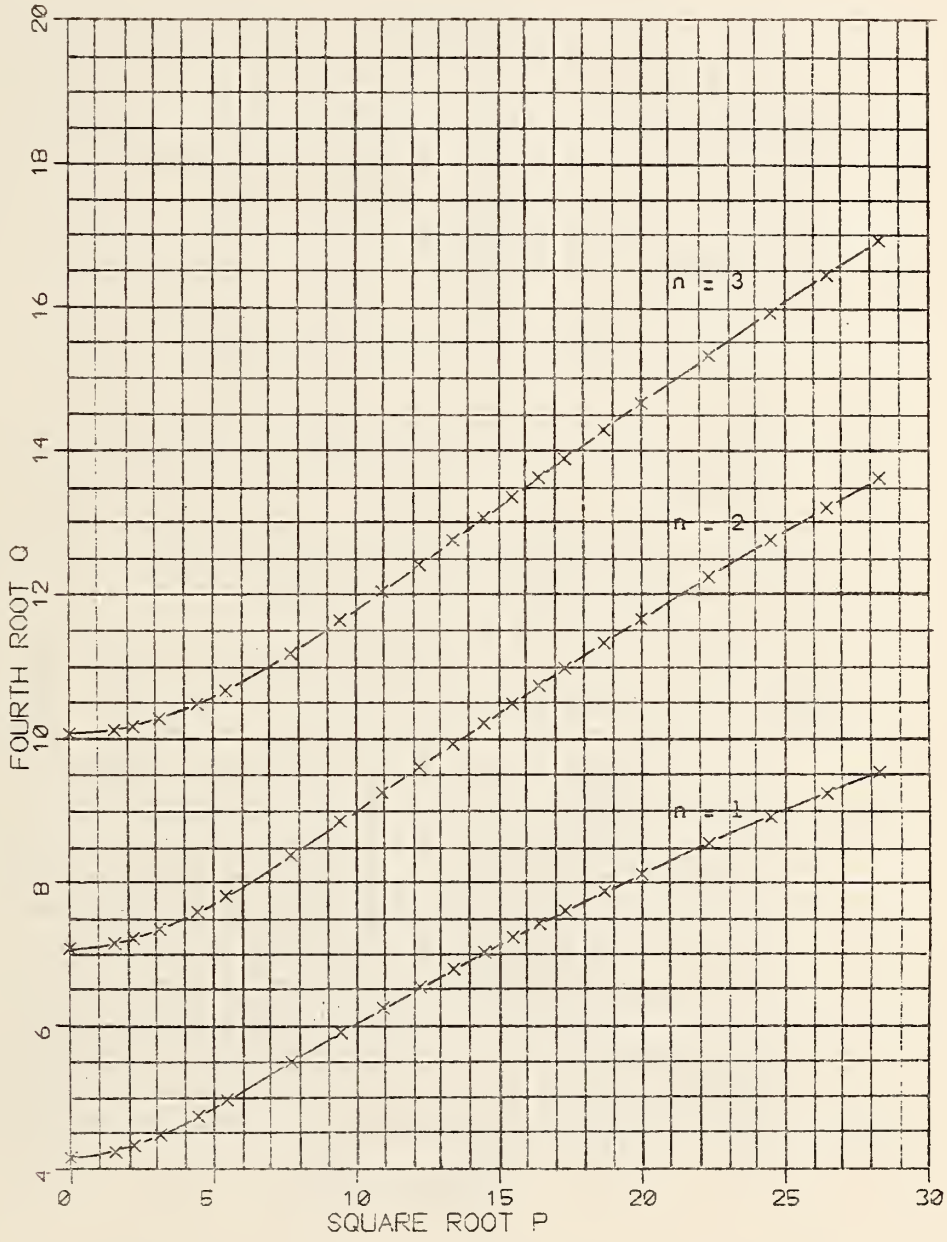


FIG. 3 NATURAL FREQUENCY AT DIFFERENT TENSION
SYMMETRICAL BEAM WITH $\sigma = 10$

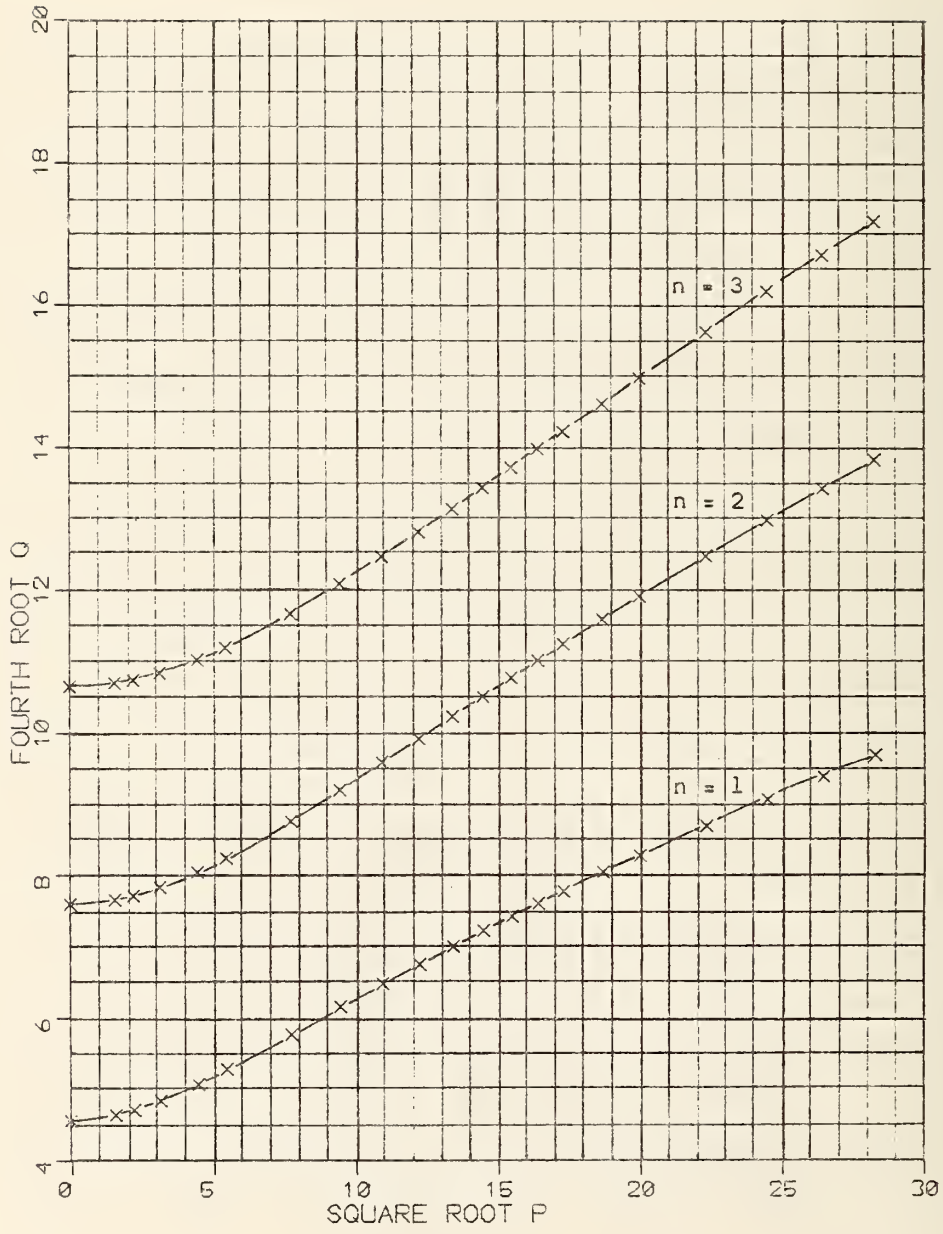


FIG. 4 NATURAL FREQUENCY AT DIFFERENT TENSION

SYMMETRICAL BEAM WITH σ=50

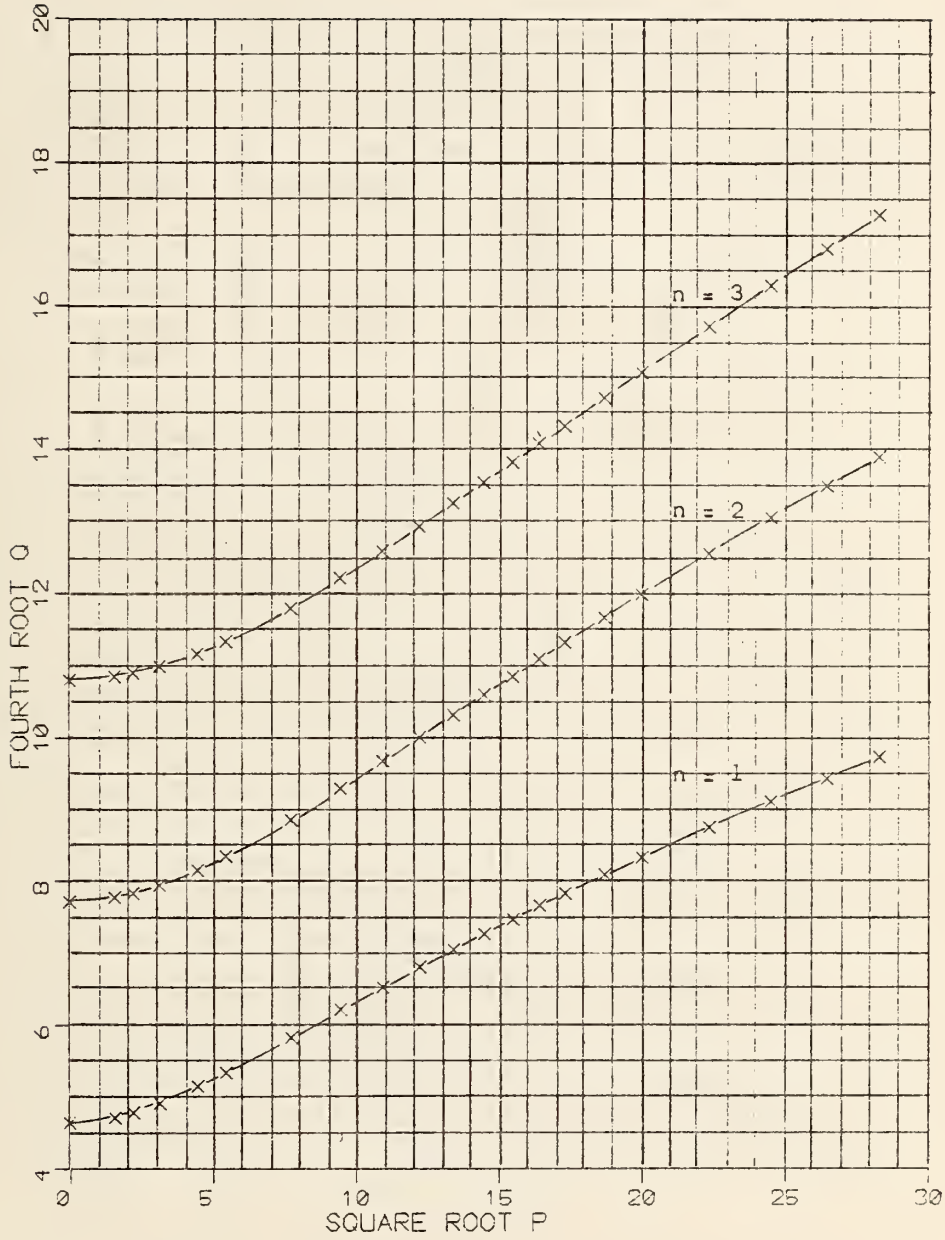


FIG. 5 NATURAL FREQUENCY AT DIFFERENT TENSION

SYMMETRICAL BEAM WITH σ=100

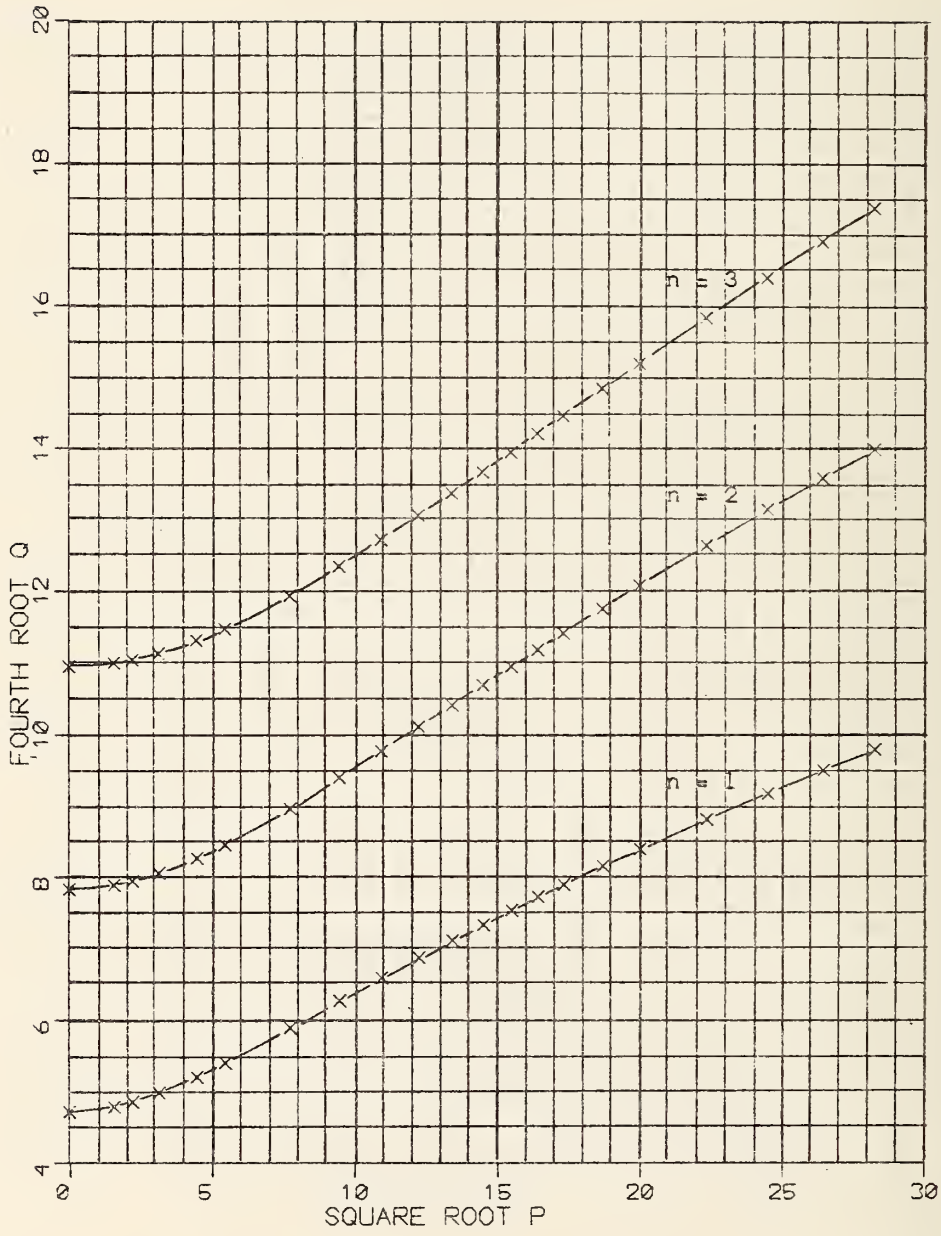


FIG. 6 NATURAL FREQUENCY AT DIFFERENT TENSION

SYMMETRICAL BEAM WITH $\sigma_{\cdot}$=500

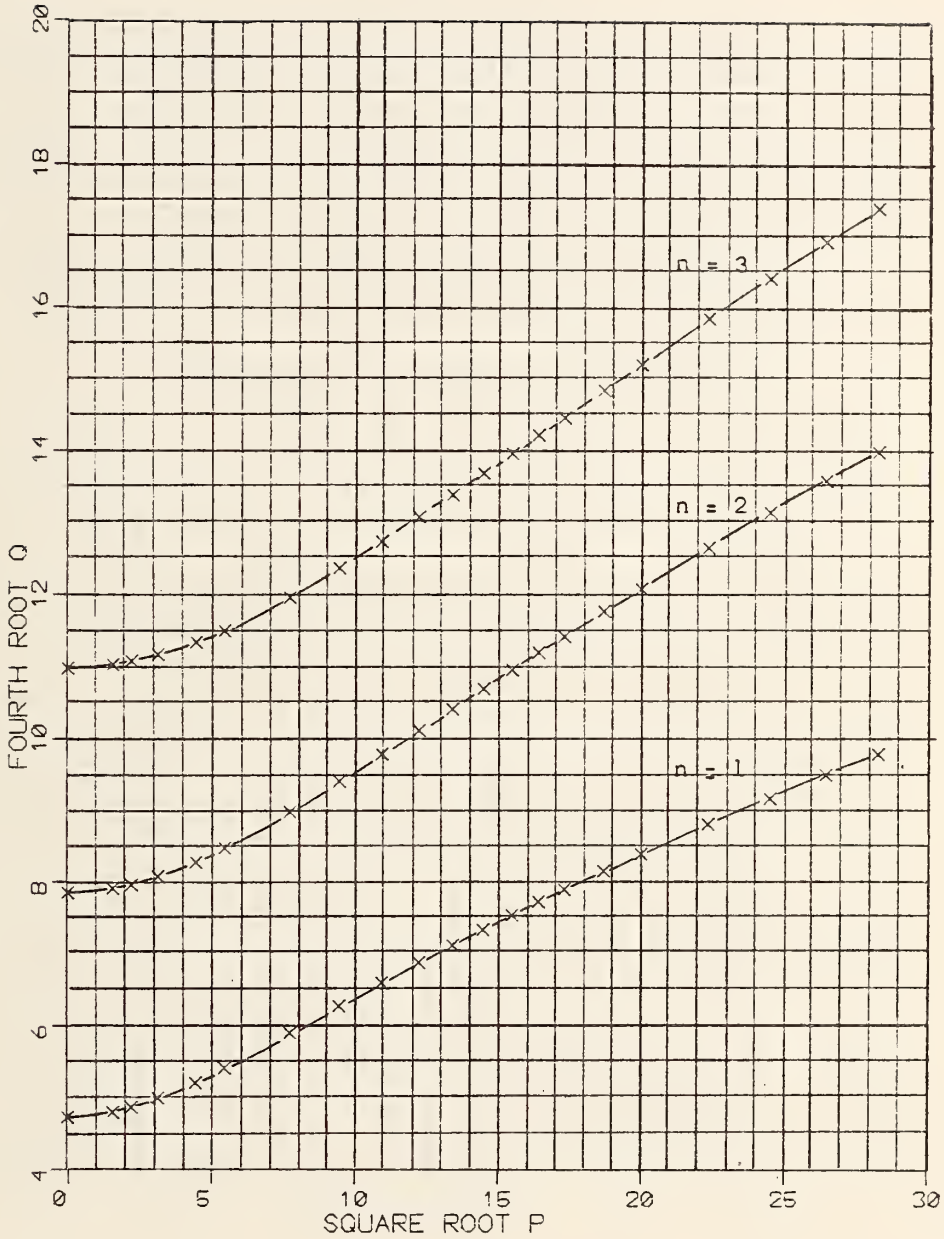


FIG. 7 NATURAL FREQUENCY AT DIFFERENT TENSION
SYMMETRICAL BEAM WITH σ=1000

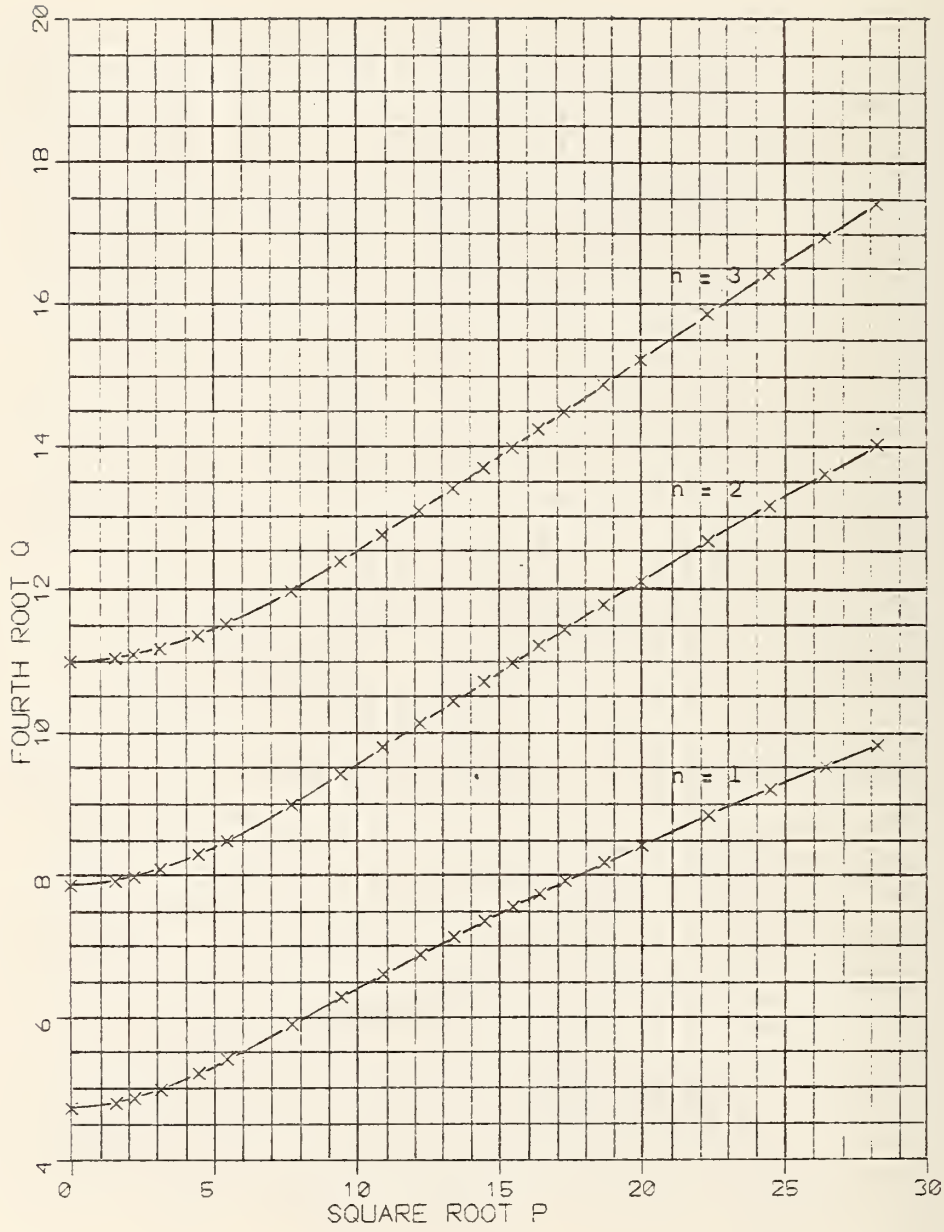


FIG. 8 NATURAL FREQUENCY AT DIFFERENT TENSION
SYMMETRICAL BEAM WITH σ=10,000

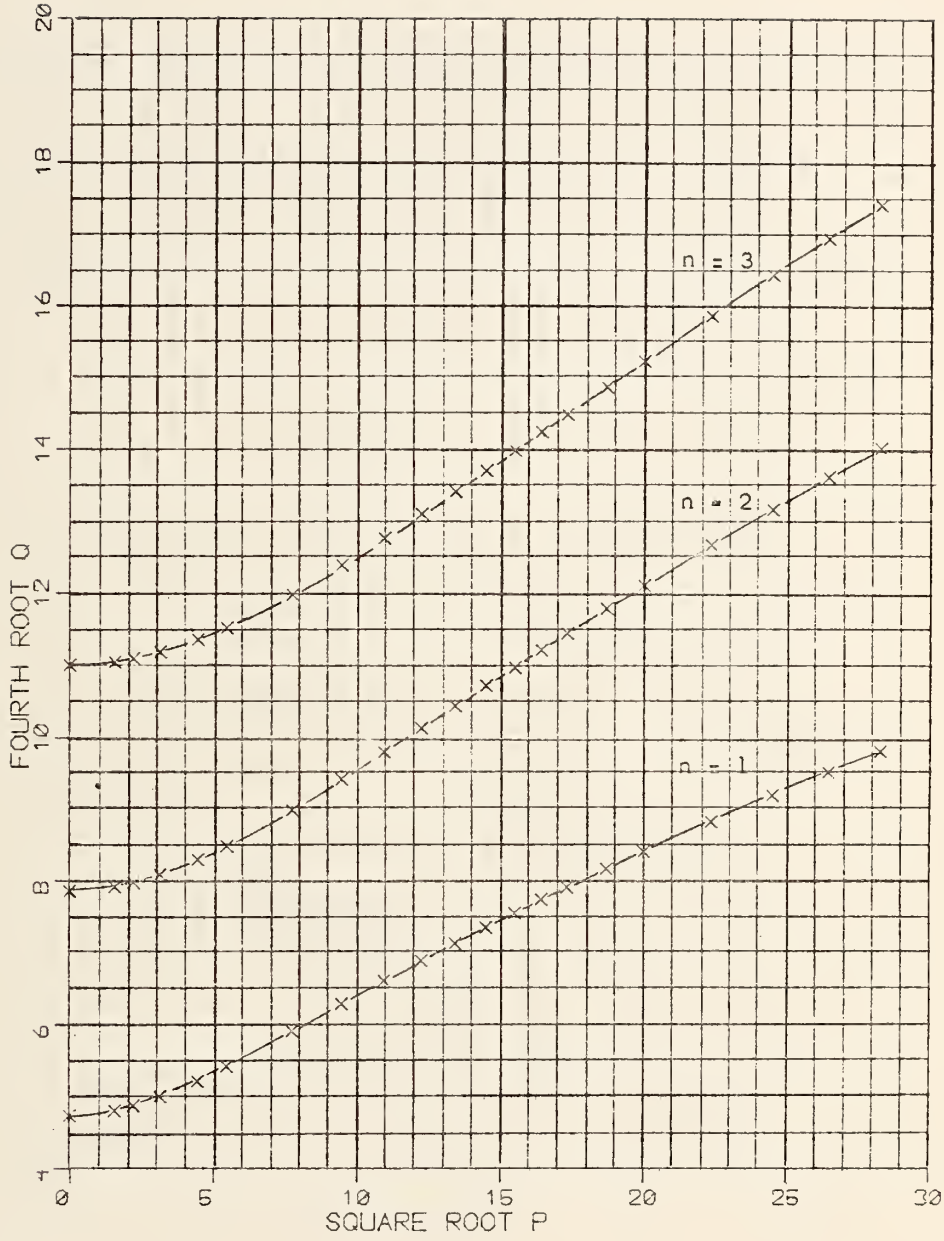


FIG. 9 NATURAL FREQUENCY AT DIFFERENT TENSION

SYMMETRICAL BEAM WITH $\sigma = 100{,}000$

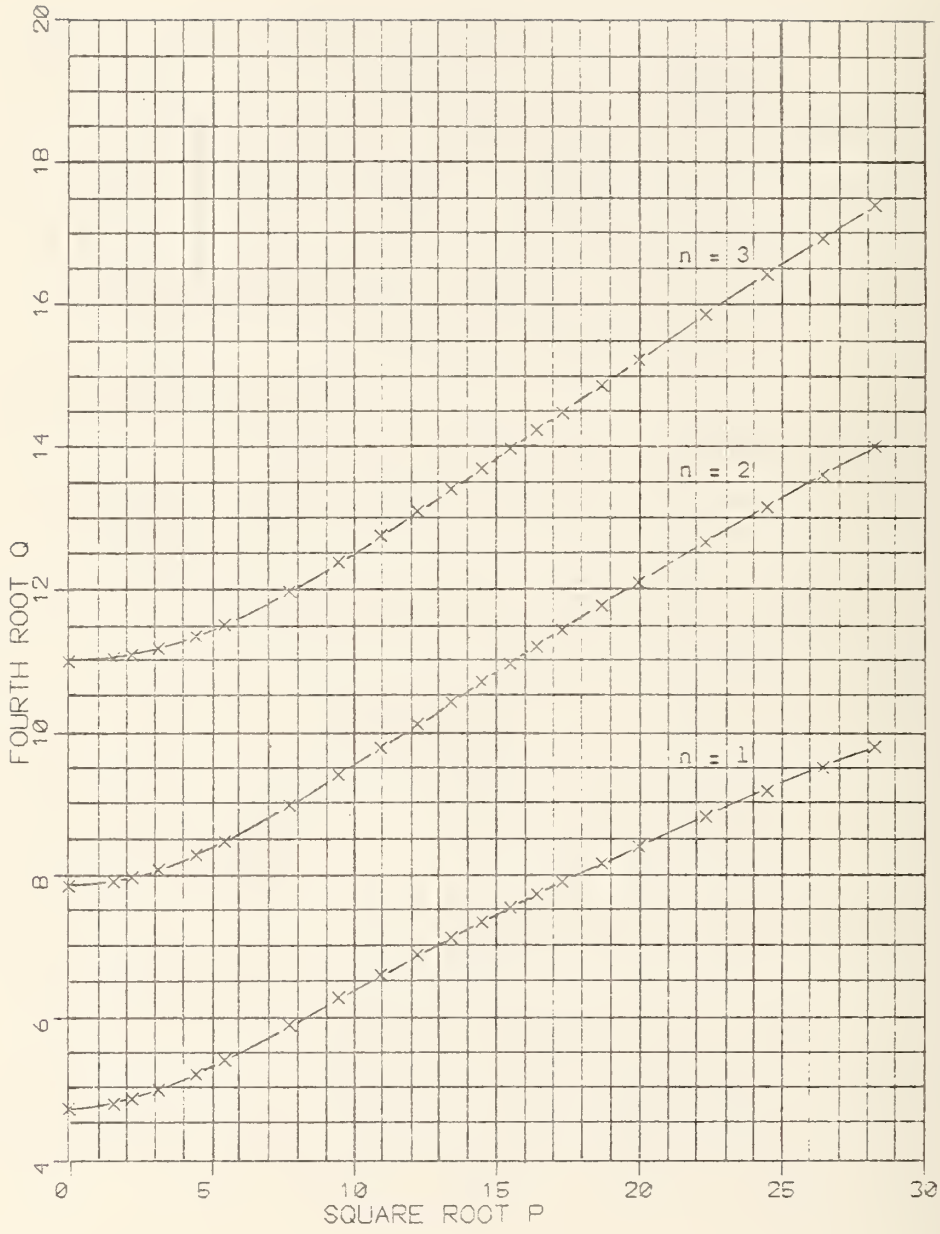


FIG. 10 NATURAL FREQUENCY AT DIFFERENT TENSION
SYMMETRICAL BEAMS WITH FIXED ENDS ($\sigma \to \infty$)

Table 1. Natural frequency coefficients for thin closed sections.

Mode No.	Natural Frequency Coefficients, $\sqrt[4]{Q}$ For Any P
1	1.77
2	2.51
3	3.07

Where

$$P = \frac{\frac{T}{A} I_p}{GC}$$

$$Q = \frac{\rho_m I_p \omega_n^2 L^2}{GC}$$

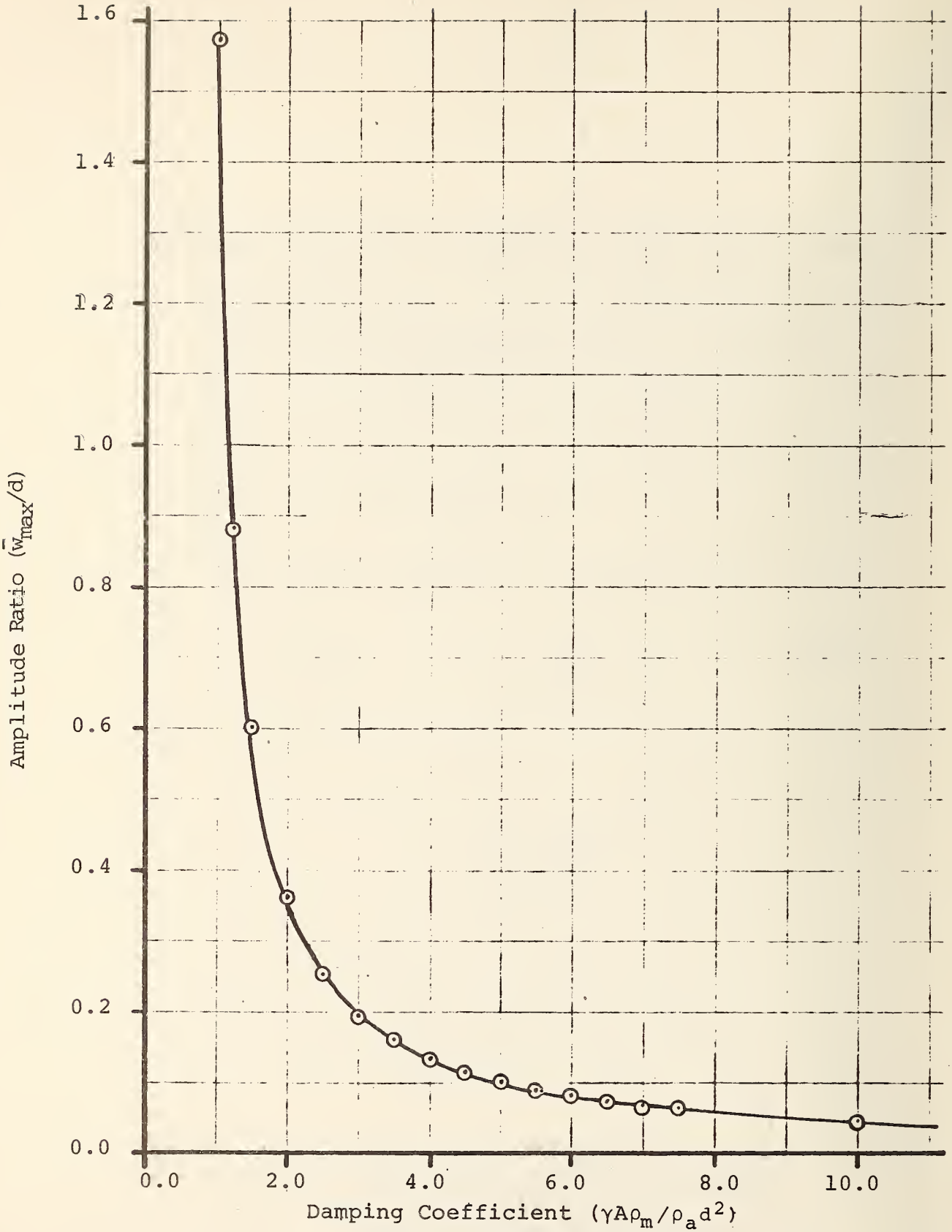


Fig. 11 Amplitude of H-Beam vs. Damping Coefficients

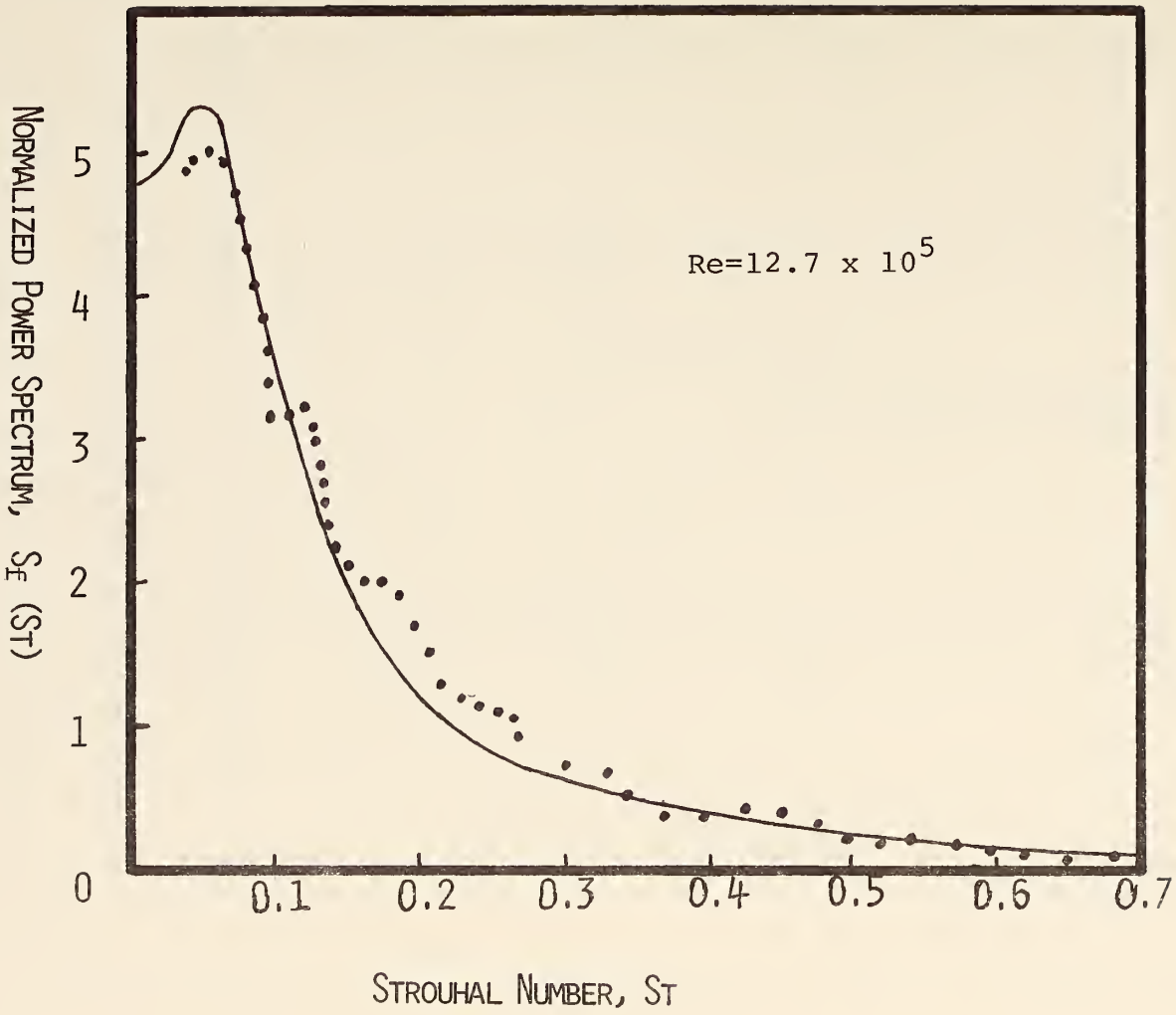


FIG.-12 POWER SPECTRUM BEHIND A CYLINDER

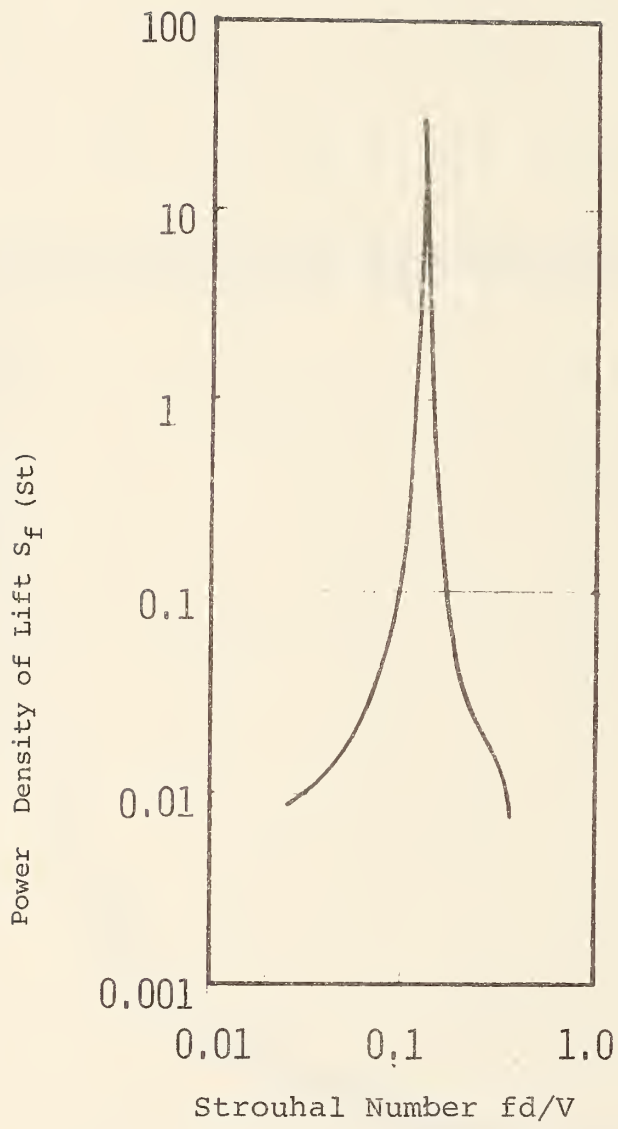


FIG. 13 A SPECTRUM OF LIFT ON A SQUARE SECTION

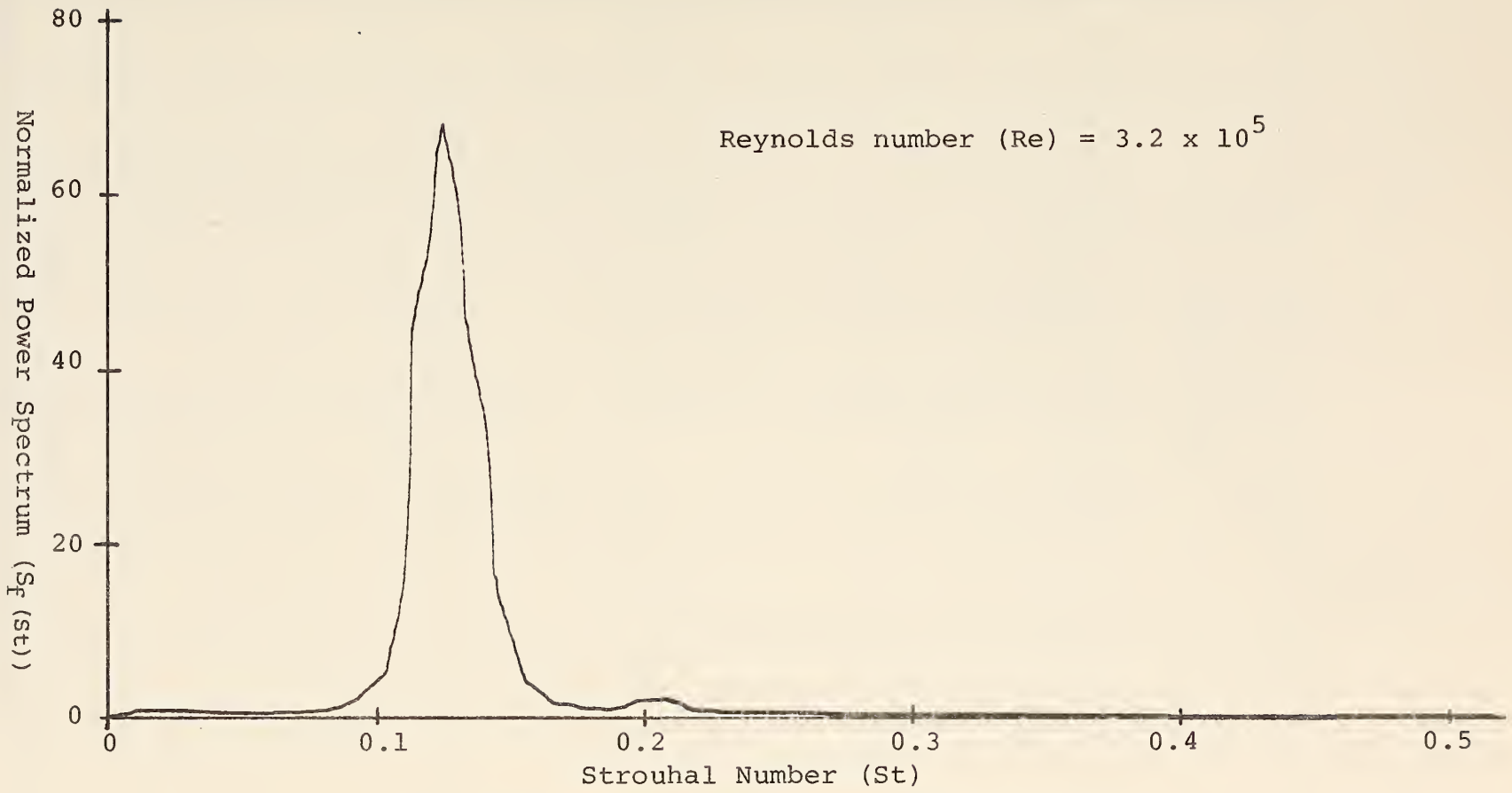


Fig. 13B Power Spectrum Behind An H-Section

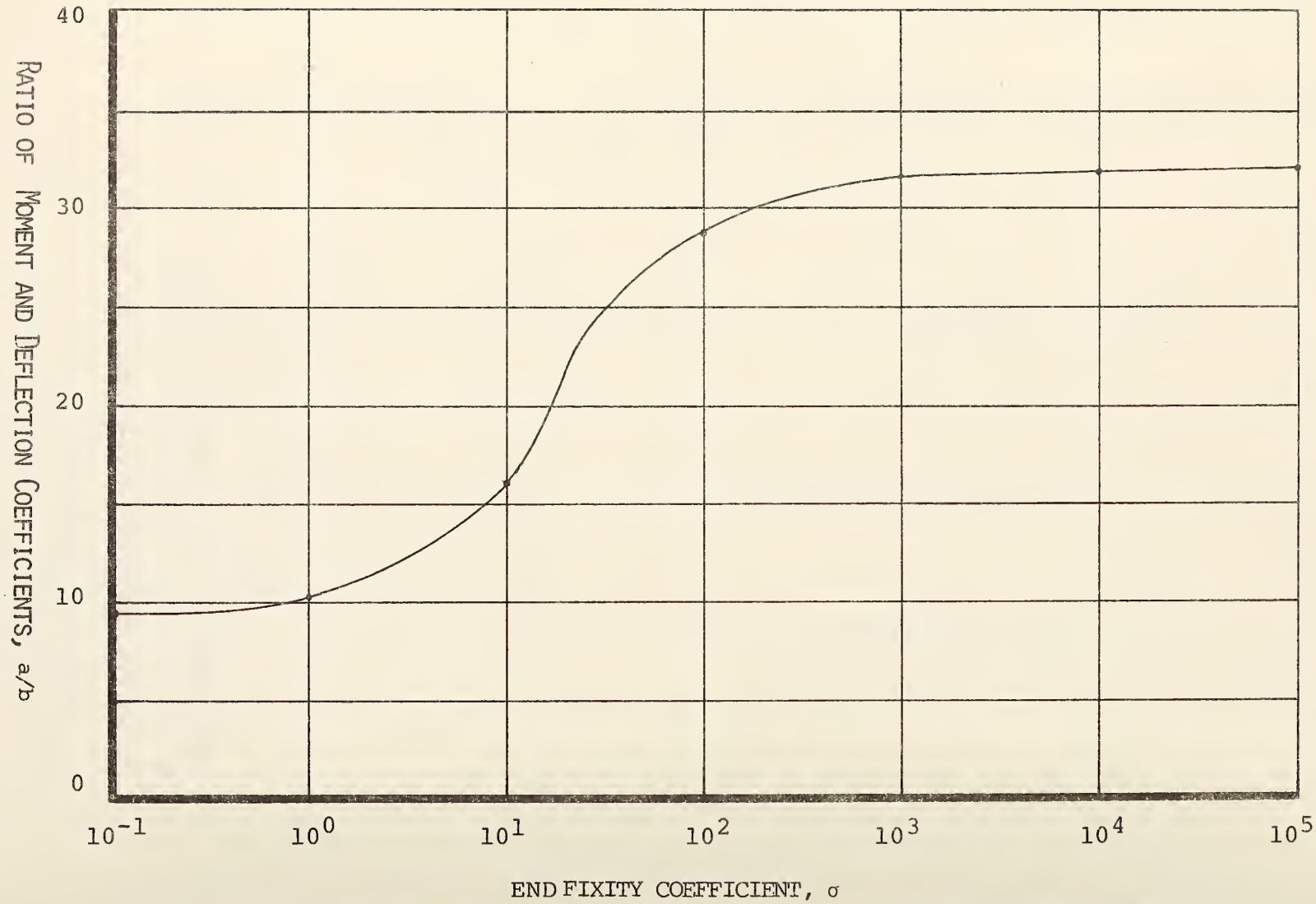


FIG. 14 VARIATION OF MOMENT-DEFLECTION COEFFICIENT AT DIFFERENT END CONDITIONS

PART A
GENERAL DISCUSSIONS

I. INTRODUCTION

In the current design practice, a dynamic wind load is accounted for by converting it to its static equivalent. The effect of gusts or even hurricane forces can be safely taken care of in this manner. The wind-induced vibrations of the bridge decks, especially the stiffening trussess in suspension bridges, have also attracted considerable attention and are carefully suppressed by stiffening the structure, and by modification of cross-sections with streamline fairings and other devices. One problem which has so far been neglected is the wind-induced vibration of individual members. The individual members can be set in vibration by wind usually through the vortex shedding phenomenon. If the exciting frequencies happen to coincide with natural frequencies of the structural members, rather severe vibrations can take place, even in moderate wind velocities and intensities. Ironically, it is often the moderate wind that can cause more damages because of its more commonplace occurrence, rather than the severe ones, which are rare events. For instance, it is conceivable that a mild wind of 20 knots can occur perhaps 100 days per year. A typical bridge member in question would undergo stress reversals of nearly 2×10^8 cycles per year! Fatigue cracks can easily develop due to this within a short

period of time, especially near the holes, re-entrant corners and other areas of stress concentrations. Violent wind induced vibrations have been actually observed in many bridge members and occurrences of these cracks of this type have been discovered in a number of them. This report attempts to analyze the causes and summarize possible remedies to this problem.

II. HISTORICAL BACKGROUND

The fact that a taut wire can be induced into vibration by a wind stream was known since antiquity, as evidenced by the use of the aeolian harp as a music instrument by the Greeks as early as 300 B.C. The general phenomenon was first investigated by Strouhal in 1878. In his experiments a taut wire was attached to a revolving frame about a parallel axis. It was found that the pitch of the aeolian tone was independent of the length and of the tension of the wire, but to vary with its diameter and the speed of the motion relative to the air. He also observed that the intensity of sound was greatly enhanced when the speed was such that the aeolian tone coincided with one of the "Proper tone" of the wire and that, other conditions being the same, the rise of temperature in the air caused a slight but appreciable fall in pitch.

It had been generally assumed that the excursion of the wire would be in the direction of the wind stream. It was Lord Rayleigh who placed a taut wire near the exit of chimney draught and observed that the vibrations were effected in a plane perpendicular to the direction of the wind. The existence of a vortex sheet was known to Leonardo da Vinci in the fifteenth century who sketched a row of vortices in the wake of a bluff body in a stream. Lord Rayleigh associated the production of the tone with the vortex sheets. He also explained that the effect of temperature on the aeolian tone was due to the change of viscosity (which

implied that the Strouhal frequency must be a function of the Reynolds number; of course, the latter term was unknown to him).

The wake behind a bluff body was analyzed by Helmholtz and Kirchhoff, but the results were not in agreement with the experimental findings by Prandtl. An independent approach was used by Kármán and Föppl, who left the origin of the vortex sheet unanswered but addressed to the question: what are the stable arrangements of vortices behind a bluff body? Kármán found that, for infinitely long straight vortex streets in two rows, the only stable arrangement is when the ratio between the row spacing and the spacing between individual vortices equals 0.281 in a staggered arrangement. Föppl found that a pair of fixed vortices of suitable strength could maintain a symmetrical equilibrium position behind a circular cylinder, provided that they are not subjected to any asymmetric disturbances.

Kármán's work motivated much theoretical work to extend his theory and experimental work to determine the validity of his stability criterion. The space ratio has been generally confirmed by his own work and others in the early years. The drag coefficients were in much better agreement with the Prandtl's results than Kirchhoff's even though it is still somewhat on the low side. It appeared that a good working rule was available even though the exact mechanism which causes the vortex shedding was still not well understood.

Since about 1950, a number of carefully conducted experiments were designed to study the formation of vortex streets. The

main effort was aimed at the study of precise dependence of vortex shedding on the Reynolds number at the extreme ranges. At the low range of Reynolds number, it was found that the "attached" vortex pair postulated by Föppl does exist but becomes unstable as the Reynolds number increases beyond 40. This wake instability is responsible for vortex shedding whose longitudinal spacing differs from the Kármán's criterion, and whose individual vortices are laminar and are preserved for many diameters downstream.

It was found that the shear layers at the boundaries of the wake springing from both separation points became turbulent as the Reynolds number increased to 100 and rolled up into vortices to form a vortex street. The individual vortices gradually became turbulent in the range of Reynolds number of 150 to 300 depending on the extent of disturbance. Beyond that, the vortex street became fully turbulent and the vortices diffused rapidly as they moved downstream. The process remained essentially similar until Reynolds number reached the neighborhood of 3×10^5 at which the boundary layer itself on the cylinder reached the transition zone. The Strouhal number remained essentially constant in this region.

In the transition zone, the wake width became narrow and the separation points moved further downstream around the cylinder. This resulted in a very rapid increase of the conventional Strouhal number with Reynolds number. The amount of

increase was related to the extent of the motion of the cylinder. The increase was found to be very large, if the cylinder was held stationary. There was no well defined vortex street in this zone, and only random shedding took place.

For Reynolds number above about 6×10^6, it was observed that there was a sudden decrease in Strouhal number and a reappearance of a vortex street. It seems that proper periodicity does not exist in the turbulent stream above transition. One may speak of a Strouhal number spectrum rather than a single value. The predominant Strouhal number was determined to be less dependent on the Reynolds number and remained essentially constant. The magnitudes of the dominant Strouhal numbers were considerably higher at the high Reynolds numbers than the subcritical case.

A very important observation made by Fage and Johansen was that the shedding frequency is related not to the diameter of the cylinder but to the width of the wake. This led Roshko to discover the existence of a universal Strouhal number which is based on the wake width, i.e., the distance between shear layers (rather than the diameter of the cylinder) and the wake velocity, i.e., that of the free shear layer (rather that the stream velocity at infinity). This number is essentially constant for not only any Reynolds number but also for any common cross-sections. This constant value is 0.16, see Figure 15.

Motivated by these observations, Birkhoff derived theoretically that for a two dimensional inviscid fluid, the Strouhal

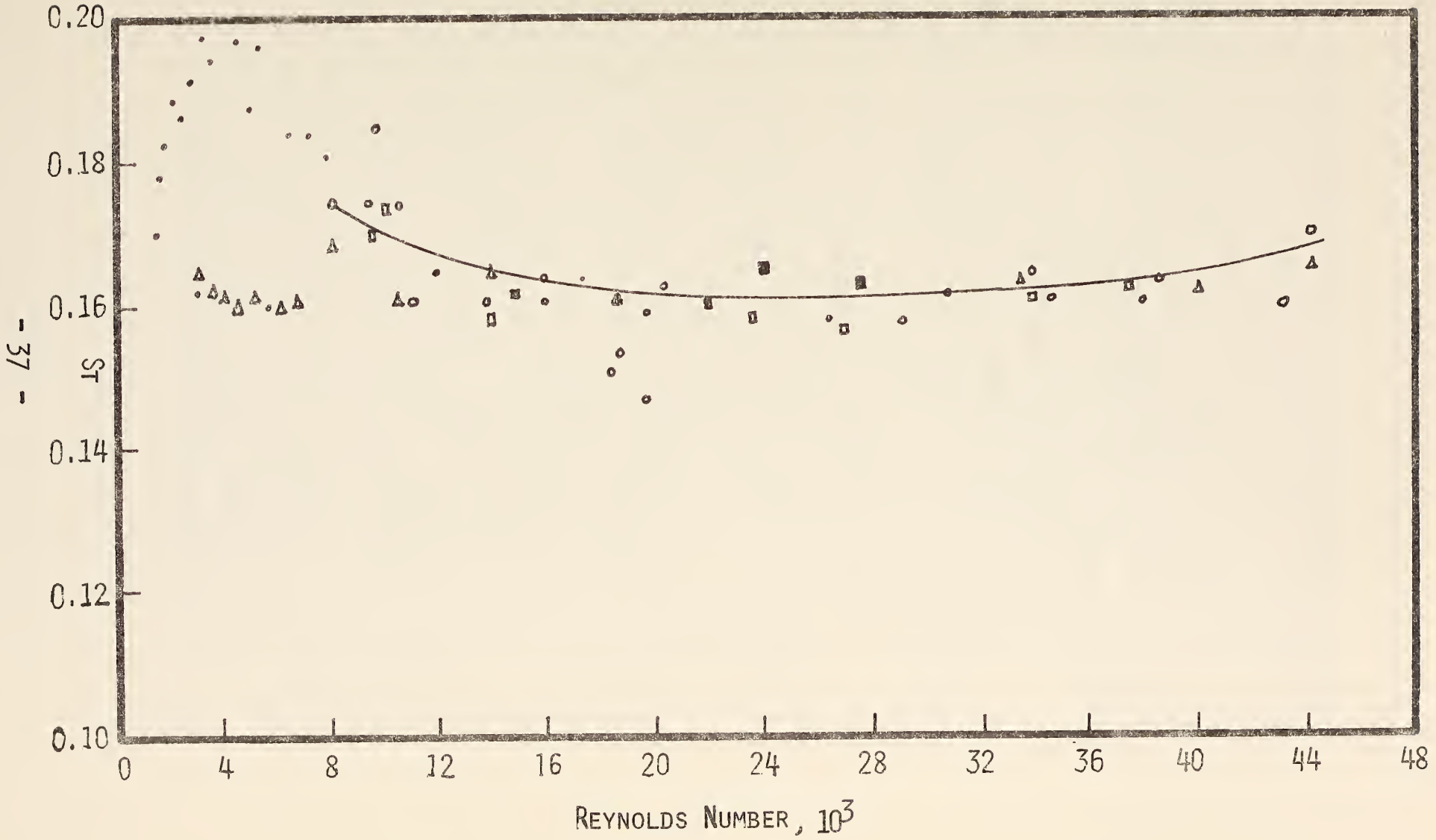


Fig. 15 Universal Strouhal Number

frequency is inversely proportional to the geometrical mean of the wake width and the vortex formation length, i.e., the average length of waving portion of the wake before the shear layers curl up to form a vortex. This approach, while more complicated, is able to explain many observed phenomena that contradict the classical findings.

So far the discussion of contemporary investigations has been concerned with a stationary cylinder, i.e., the cylinder is held steadfast so that it cannot move in response to the cross flow forces resulting from the vortex shedding. To idealize the real situation, in recent years, experiments have been conducted that employed spring-supported rigid cylinders. It was found that, as long as the natural frequency of the system is far removed from the Strouhal frequency, the cylinder would vibrate with very small amplitudes. When they are near each other, linear resonance would occur to cause moderate amplitude vibration with an eddy shedding at each end of its oscillation cycle. In circumstances in which the vibrating velocity is comparable to the stream velocity, various nonlinear phenomena occurred more frequently in cross-sections having smooth edges and tend to diminish in cases involving sharp trailing edges. Also, the sharp rise of Strouhal number at supercritical range, i.e., Reynolds number ranging from 1×10^5 to 3×10^6, does not occur as long as the cylinder is free to respond to the cross flow forces. The cylinder vibrates at the "correct" Strouhal frequencies in such cases.

When the cylinder was set in a forced vibration, there was also a range of frequencies near the natural frequency where the forced transverse vibrations synchronize or lock-in with the vortex frequency to control the shedding process. It was observed that this synchronized vibration delayed the initiation of turbulence in the wake for Reynolds numbers up to 350. The flow is essentially two dimensional with virtually no appearance of low frequency irregularities that are characteristics of the wake behind a stationary cylinder at low Reynolds number.

III. MECHANISM OF VORTEX SHEDDING

The overall flow pattern around a circular cylinder with increasing Reynolds numbers is shown in Fig. 16.

At extremely low Reynolds numbers, say less than 3, the flow follows the Stokes' law similar to a small particle settling in a colloidal solution. The streamlines will go around the cylinder except the two which connect to the stagnation points and the flow pattern is symmetric with respect to the cylinder in upstream and downstream sides. There is no wake in this range.

At the Reynolds number of 5 to 10, the upper stream side remains about the same with no significant change of pattern but at some points on the circumference of the cylinder, the boundary layers start to separate in more or less symmetrical fashion. The separated boundary layers beyond the separation points on the

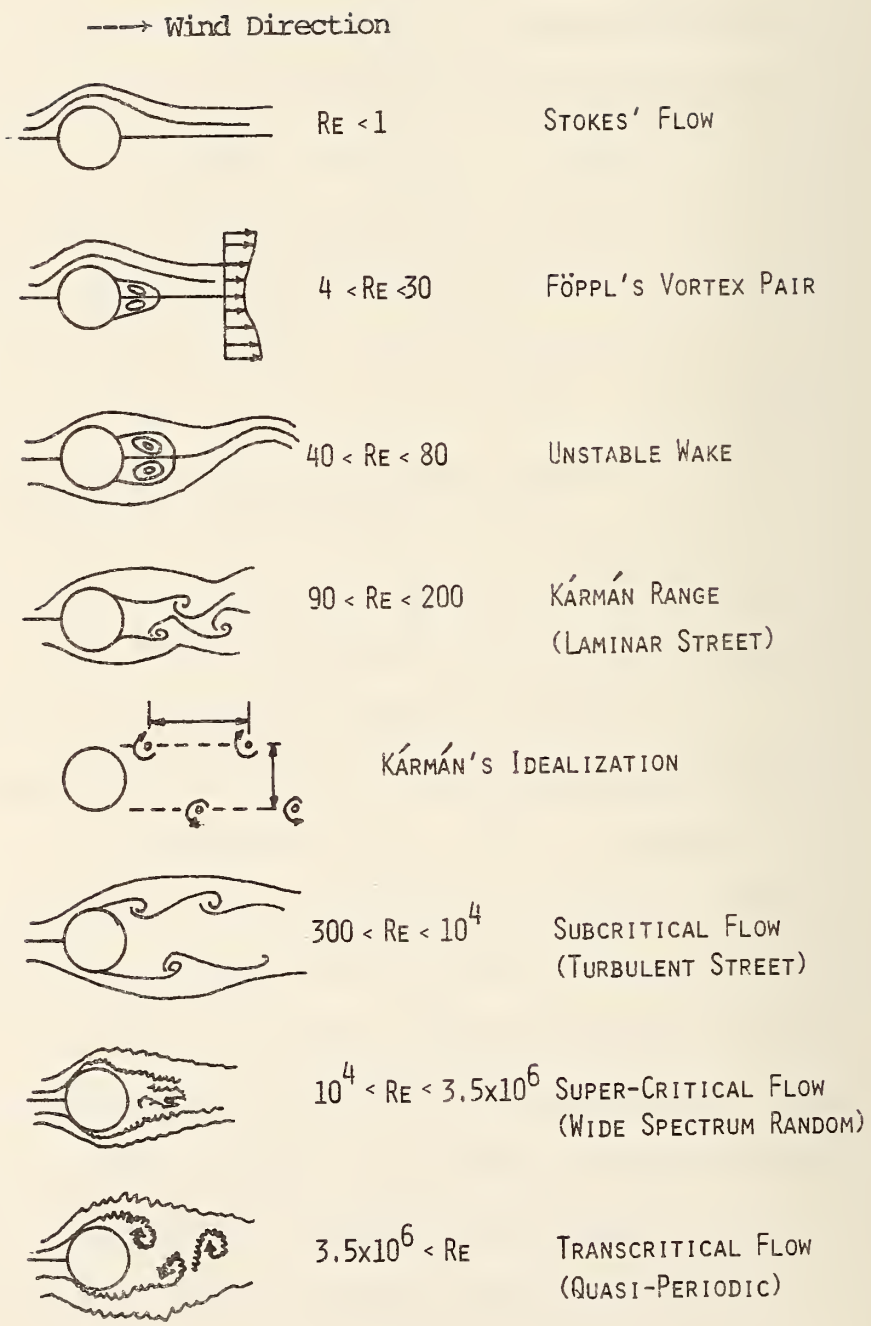


Fig. 16 Characteristic Wake Pattern at Different Re.

cylinder become shear layers or vortex layers, forming a wake behind the cylinder. The wake is a closed one since the shear layers rejoin together somewhere downstream. Inside the closed wake, two fixed vortices are formed immediately behind the cylinder. These are the Föppl vortex pair as discussed previously. This pattern is stable up to a Reynolds number of about 40, as long as there is no asymmetric disturbance. The Föppl's vortex pair can be caused to shed at lower Reynolds number by giving the cylinder a crossflow displacement.

The wake downstream from the fixed vortex pair becomes unstable at Reynolds number of about 40 and begins to shed. This is called the low speed shedding or shedding due to wake instability. The spacing ratio between the adjacent vortices is different from the value 0.281 by virtue of Kármán's theory. The wake undergoes a periodic motion rather than turbulence.

At about Reynolds number 90 the detached shear layers after its separation from the cylinder start to fold up into concentrated vorticities. This is called the high speed shedding. As usual, the transition zone cannot be precisely defined. For a range of Reynolds numbers, say between 60 to 120, the flow pattern may switch back and forth between the high and low modes of shedding causes irregularities in the longitudinal spacings of the vortices. The fluid in the vortices, however, is laminar and the vortex street persists for many diameters downstream.

As the Reynolds number is increased to the 150 to 300 range, the shear layers beyond the separation points on the cylinder

reach the transition zone and become turbulent (even though the boundary layer attached to the cylinder is still laminar). The resulting vortices, consisting of turbulent fluid, diffuse rapidly as they move downstream. The transition is complete at a Reynold number about 300.

Beyond the transition zone, the transitional point moves closer to the separation point. The distance between them depends on the upstream disturbances. The flow pattern remains essentially unchanged at least up to Reynolds numbers of 10,000 and presumably up to the transition zone of the boundary layer on the cylinder, which is Reynolds number about 2×10^5.

When the boundary layer becomes turbulent, its separation point moves further around and the wake width becomes narrower. If the cylinder remains stationary, the separation point moves back and forth around the cylinder. The turbulent wake is associated with a spanwise mixed flow. That is, the boundary layer consists of alternate spanwise regions of laminar and turbulent flow with different separation points.

For Reynolds numbers in the range of 2×10^5 and 3×10^6 the boundary layer is undergoing a transition and the wake is disorganized. The formation of the vortex street is suppressed. The energy in the eddies is more random and is spread over a much wider bandwidth of frequency. Beyond Re = 3×10^6, the boundary layer is fully turbulent. More regular periodicity recurs and a more or less regular vortex street is

restored. The separation line on the rear of the cylinder becomes wavy, showing streaks of three dimensional boundary layer flow. Compared with the transition zone, the excitation in full turbulent flow is more regular and it may be called "narrow-band random" or quasi-periodic. At Reynolds number of 10×10^6, the separation line becomes straightened and moves slightly upstream. Meanwhile the disturbance at the rear face of the cylinder gradually disappear at higher Reynolds numbers. This suggests that at even higher Reynolds number, the quasi-periodic pattern should prevail. There is no evidence to verify this, partially because of the extreme difficulties in conducting experiments in a high Reynolds number regime such as the larger throat area and high pressure requirements.

The boundary layers after separating from the cylinder become free shear layers. After several diameters the shear layers roll up to become the vortex street. This stretch is called the formation length. The flow pattern is very sensitive to the disturbance there. The flow pattern will be changed if fluid is injected into the wake. This can be easily done through the body itself. This technique has been given the term base bleeding. For low bleeding rates, the wake narrows down as if the body were elongated into the wake. At higher bleeding rates the wake is widened. For very thin cylinders, say ½ mm in diameter, the pattern is disturbed even by insertion of a hot wire in the shear layer.

There is evidence which indicates that the free shear layers from either side of the wake interfere with each other in the formation length. If a thin partition is placed along the centerline of the wake, downstream of the cylinder, the pattern of flow will be changed. This technique has been given the term "splitter plate". If the length of a splitter plate is long, the vortex formation is totally prevented. For a short plate, placed near the cylinder, the effect is similar to low base bleeding and the vortices form downstream from the splitter plate. This downstream shift of formation location tends to narrow the wake. On the other hand, when the plate is placed far downstream beyond the formation length, the vortices form in normal way and no change in flow pattern is observed. Pressure measurement showed that the minimum pressure was moderated by the presence of the splitter plate and its location moved further downstream.

The flow pattern is also sensitive to the surface condition of the cylinder such as roughness. The cause may be attributed to interference with the separation line. Experiment showed that by placing trip wires on the surface of the cylinder, the separation line can be significantly altered. It was found that, regardless of the disturbance, a vortex street can exist as long as a more or less straight separation line can be maintained on the cylinder surface. Vortex-shedding can be virtually inhibited by a crisscross arrangement of trip wires, for which a straight separation line is impossible.

The width of vortex street is not exactly constant. Careful observations show that the transverse spacing between the vortex rows first increases downstream from the cylinder, then attains a maximum and finally decreases again before the street becomes unstable and disintegrates.

The growing vortex is fed by circulation from the shear layer until strong enough to begin rolling up and drawing the opposite shear flow across the wake. The approach of vorticity of opposing sign cuts off further circulation to the growing vortex, which is then shed and moves downstream .

If the section has sharp corners, the flow separation will occur there, for all different Reynolds numbers. Thus, the flow patterns will be less dependent on the Reynolds numbers. However, the section having sharp corners will have stronger vortex excitation and will be more unstable than a smooth section. This is explained by the better correlation of disturbance along the span.

Another important sectional shape parameter is the streamwise length and the shape of the "afterbody" - which is defined as the part of the section downstream of the separation points, or the sharp edge. For example, the D-section with the flat face upstream will experience large excitation while with the flat face downstream will experience a negligible excitation.

IV. STROUHAL NUMBERS

It is well known that the Strouhal Number is shape dependent. The most widely reported Strouhal Number is associated with a circular cylinder. The Strouhal Number for rectangular sections are also fairly well studied. However, for other sections, especially structural shapes, there is only scant information available in literature.

The classical Strouhal Number for a cylinder placed normal to the current is defined as:

$$St = \frac{fd}{V}$$

where St = Strouhal Number

f = frequency in Hertz

d = diameter of cylinder

V = speed of stream current

1. Circular Cylinders

For a smooth circular cylinder the relation between the Strouhal Number and the Reynolds number is shown in Fig. 17 . It is seen that it is roughly divided into six regions. Strouhal's phenomenon, as explained by Rayleigh, that Strouhal Numbers for a thin wire decreases slightly with a rising temperature, (hence, with an increase in Reynolds number) is true only in the region of Turbulent Vortex Street-Laminar Boundary Layer. For low Reynolds numbers, which comprise the Transition range, Laminar Vortex Street range, and Wake Instability Vortex Street range, the Strouhal Number decreases rapidly with the decrease of Reynolds numbers. By an empirical fitting, it

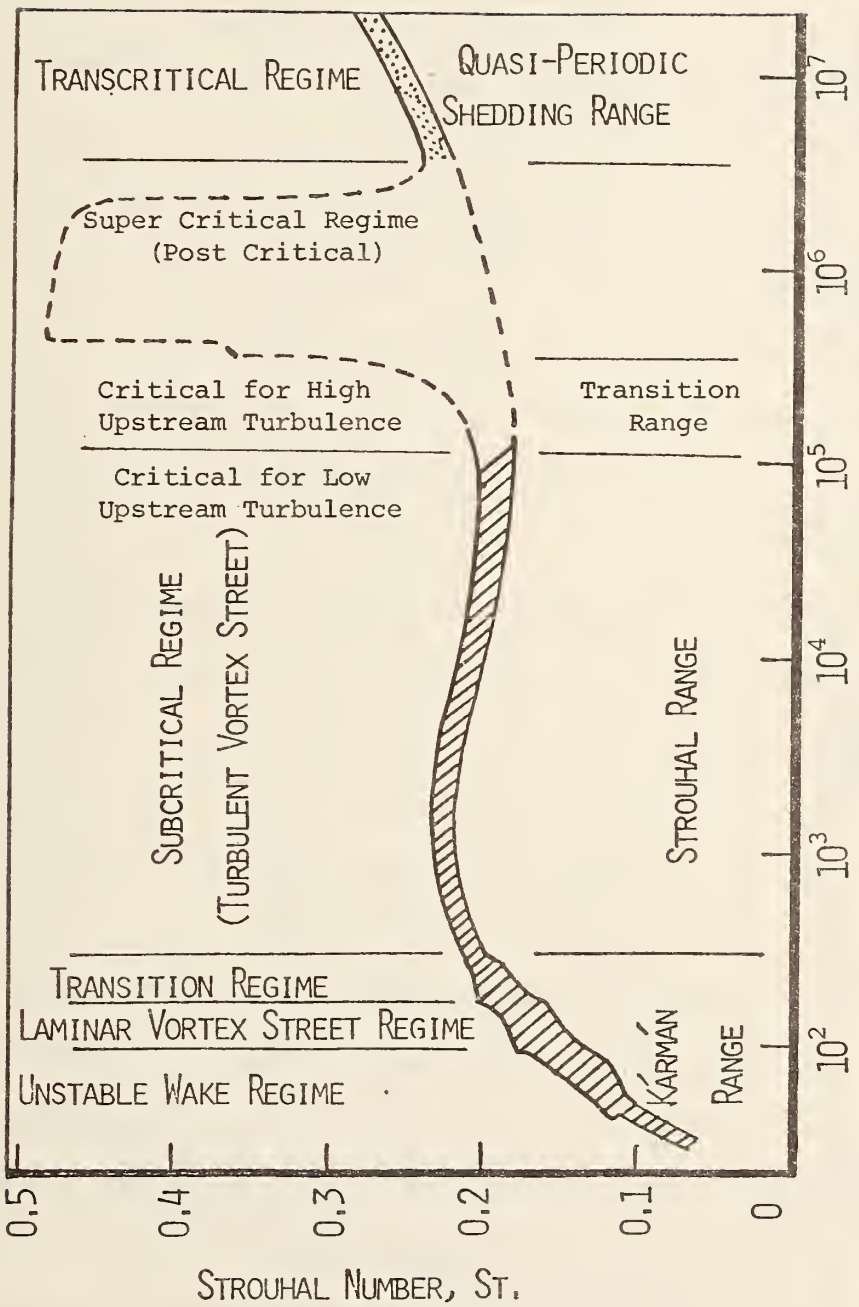


FIG. 17 STROUHAL NUMBERS OF A CIRCULAR CYLINDER VS REYNOLDS NUMBERS

was found that the following expressions hold true approximately:

$$St = 0.195 - 3.92/Re \quad \text{(Rayleigh, Tyler)}$$

but a better fit is given by

$$St = 0.212 - 4.5/Re \quad \text{(Roshko)}$$

for Reynolds number up to about 250,

and $$St = 0.212 - 2.7/Re \quad \text{(Roshko)}$$

for Reynolds numbers in the range of 250 to 2000. The detailed relationship is shown in Fig. 18 . Beyond Re = 2000, the flow is the Turbulent Vortex Street range, Strouhal Numbers appear to decrease from 0.21 gradually to about 0.18, when the flow reaches critical condition, and enters the incipient transition flow . This range was studied by Strouhal.

The exact Reynolds number at which the critical flow starts cannot be explicitly stated. It can be as high as 4×10^5, depending on the disturbances. The disturbances can originate from the turbulent flow upstream or from the irregularities on the surface of the cylinder. Extreme roughness on the surface of the cylinder will greatly advance the incipient transition flow.

In the transition range, the Strouhal Numbers can assume a wide range of values, depending principally on the support condition of the cylinder, (See Fig. 19). If the cylinder is held stationary (i.e., motionless), the Strouhal Number can be very high, with a reported value as much as 0.5. If the cylinder is free to respond to excitations, a Strouhal Number may be as low as 0.2, which was observed in cases of large smoke stacks. Various intermediate values have also been recorded and some observers insist that the shedding is

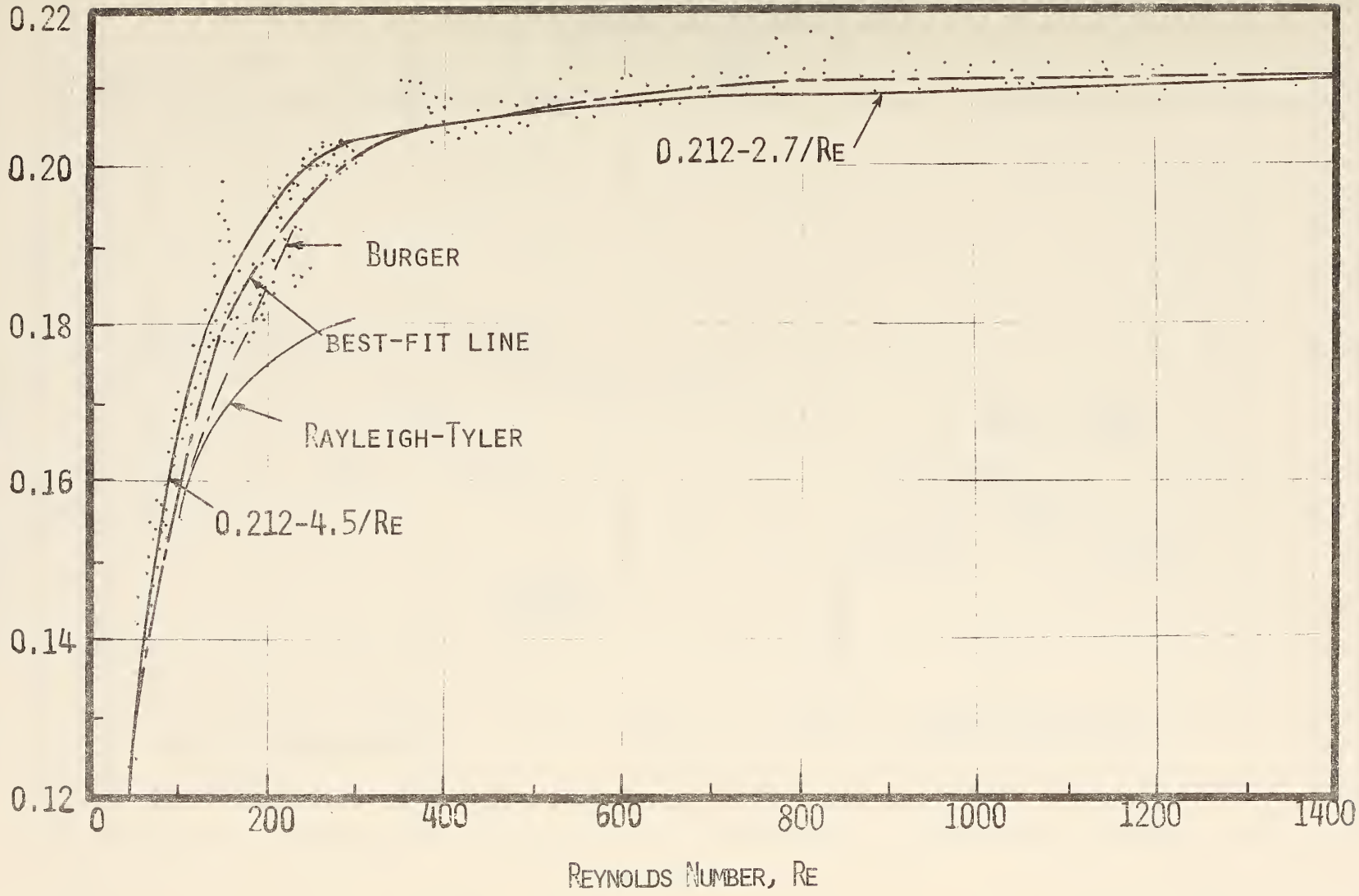


FIG. 18 STROUHAL NUMBERS OF A CIRCULAR CYLINDER AT LOW REYNOLDS NUMBERS

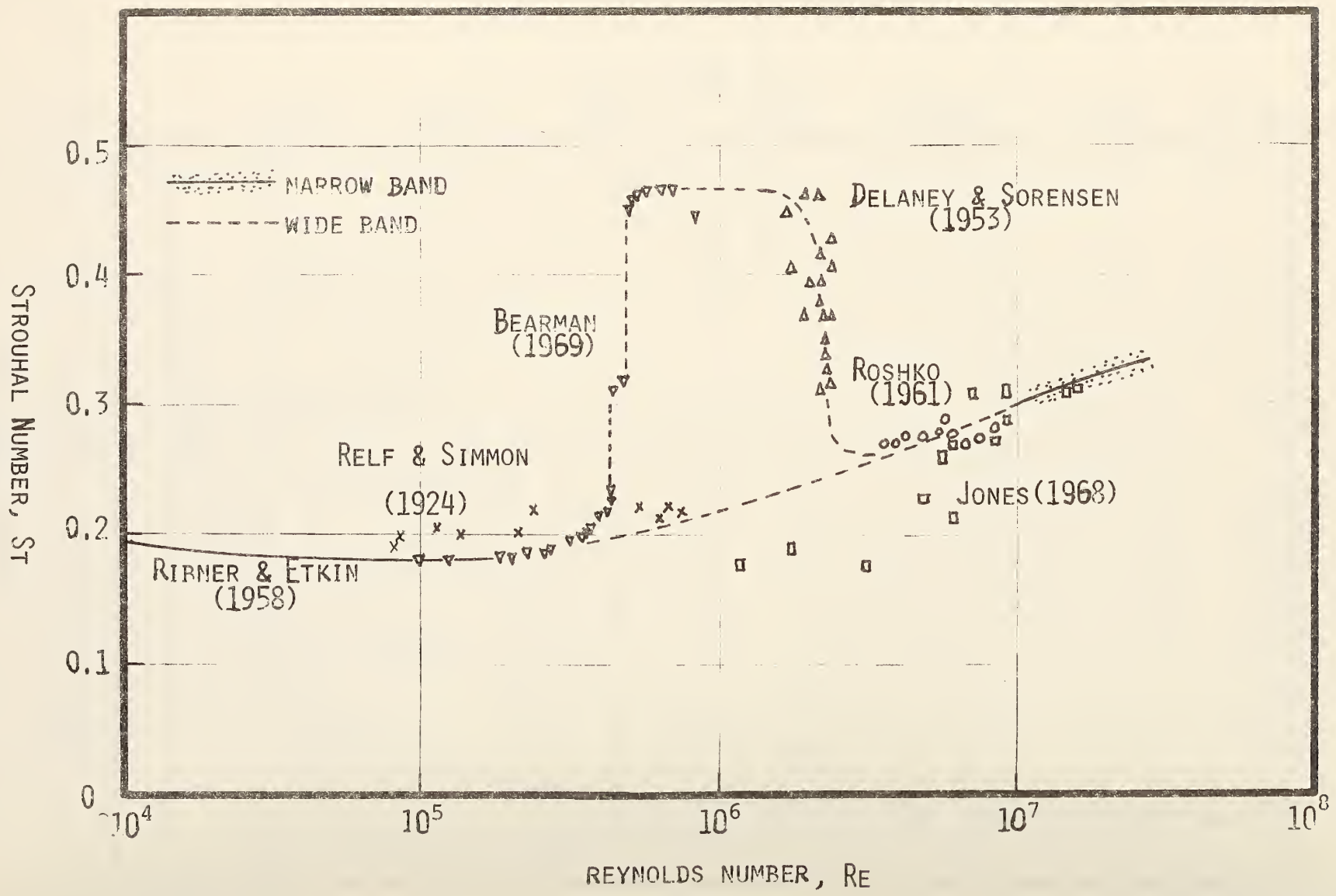


FIG. 19, STROUHAL NUMBERS OF A CIRCULAR CYLINDER AT HIGHER REYNOLDS NUMBERS

aperiodic. Observations of spectra of velocity fluctuations indicated that the shedding extended over a broad band of frequencies. Each frequency in the band carries a portion of the energy from the wind stream. The frequency which carries the largest portion of the energy is the dominant frequency at which the cylinder presumbly vibrates.

The fact that the energy is distributed over a broad band of frequencies in a transition range is of particular interest in the structural design criterion concerning wind-induced vibrations. It is clear that the energy spectrum would be flatter over a broad band of frequencies and hence the root mean square energy for any given frequency would be smaller. It is for this reason that, in a good design practice, a suitable adjustment of design parameters should be made to keep Reynolds numbers in the transition range.

The shape of energy spectrum depends on the shape of the specimen and upstream turbulence, etc., see Fig. 20. It is most probably dependent also on the support condition of the cylinder. The spectra would shift substantially downward in the frequency scale if the cylinder is permitted to vibrate with the excitations. In the current literature, investigations are limited to a small range of Reynolds numbers, and are applicable only to stationary circular cylinders.

In the Trans-critical range, pseudo-regular or quasi-periodic shedding resumes and the frequency response is narrow-banded (but not as narrow as in the subcritical range). The Strouhal Number is gradually on the rise with the increase of Reynolds number. This rise is due to the downstream shift of the separation points of the shear layer on the cylinder wall. A representative figure for the Strouhal

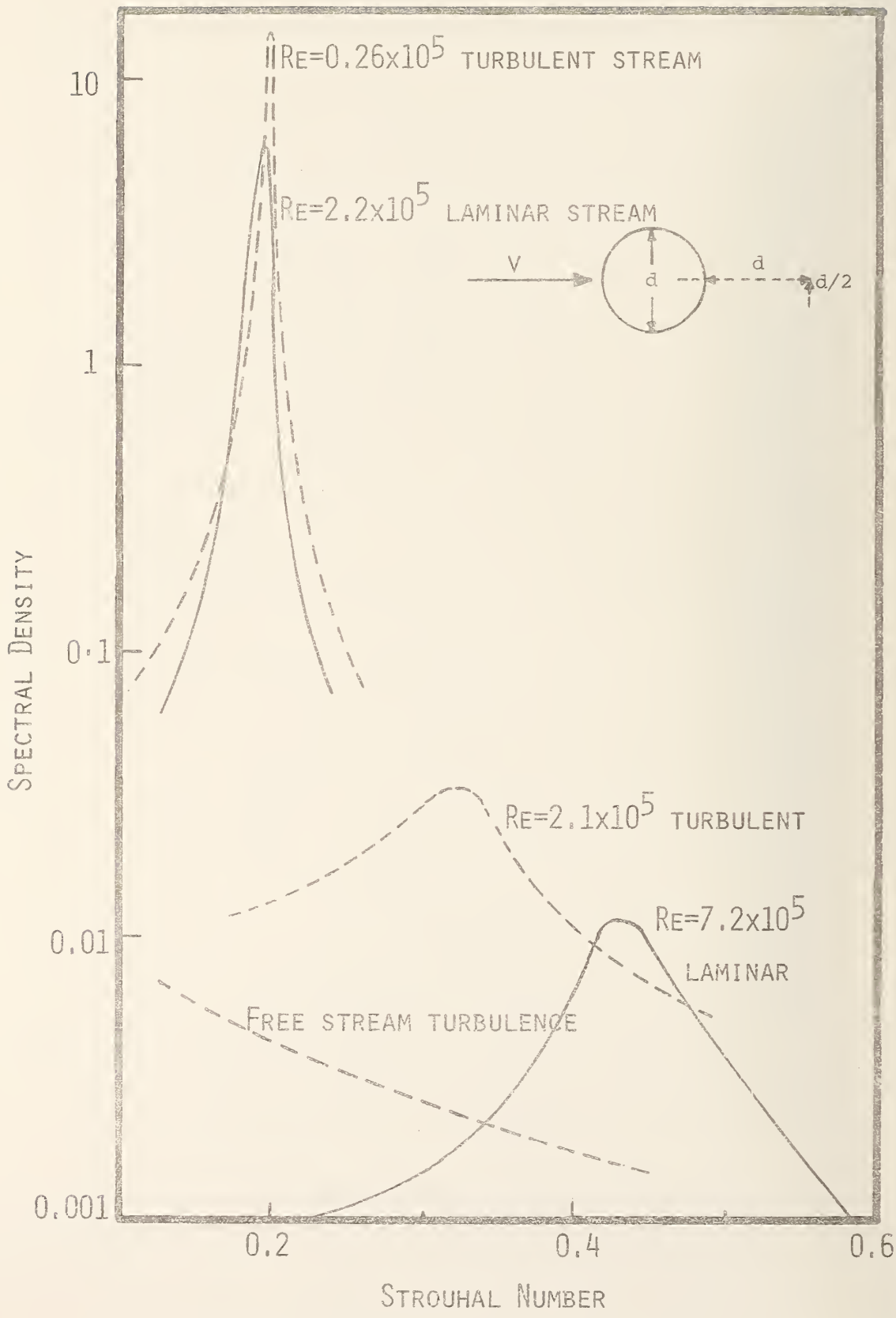


FIG. 20. SPECTRA OF VELOCITY BEHIND A STATIONARY CYLINDER

Number is 0.27 for Reynolds number = 5.0×10^6, and slightly higher for higher Reynolds numbers.

2. Rectangular Section

Two factors are important for rectangular sections: sharpness of the corners and the length of the after-body. For a truly sharp corner, the separation will always occur on the corner point, independent of the Reynolds number. Strouhal Numbers in this case will be nearly independent of Reynolds numbers. For a rectangular section which has round corners, there will be some downstream receding of the separation points at increasing Reynolds numbers, with a corresponding increase of Strouhal Numbers as a consequence of it, although this increase is more moderate in comparison to the case for a circular cylinder.

The other important sectional parameter is the streamwise length and shape of the part of the section downstream of the separation points. This so-called after-body is the part of the structure most directly exposed to the vortex excitation. A long after-body will interfere with the wake vortex formation, much like a splitter plate and can also cause the separated flow to reattach to its surface at a point further downstream. The flow may separate again after reattachment for a very long afterbody, and the vortex formation takes place in the wake of the second separation. In either case, the Strouhal Number is decisively influenced by this parameter. Fig. 21 shows the variation of Strouhal Numbers with the after-body length ratio. It is seen that the Strouhal Number assumes a constant value of about 0.14

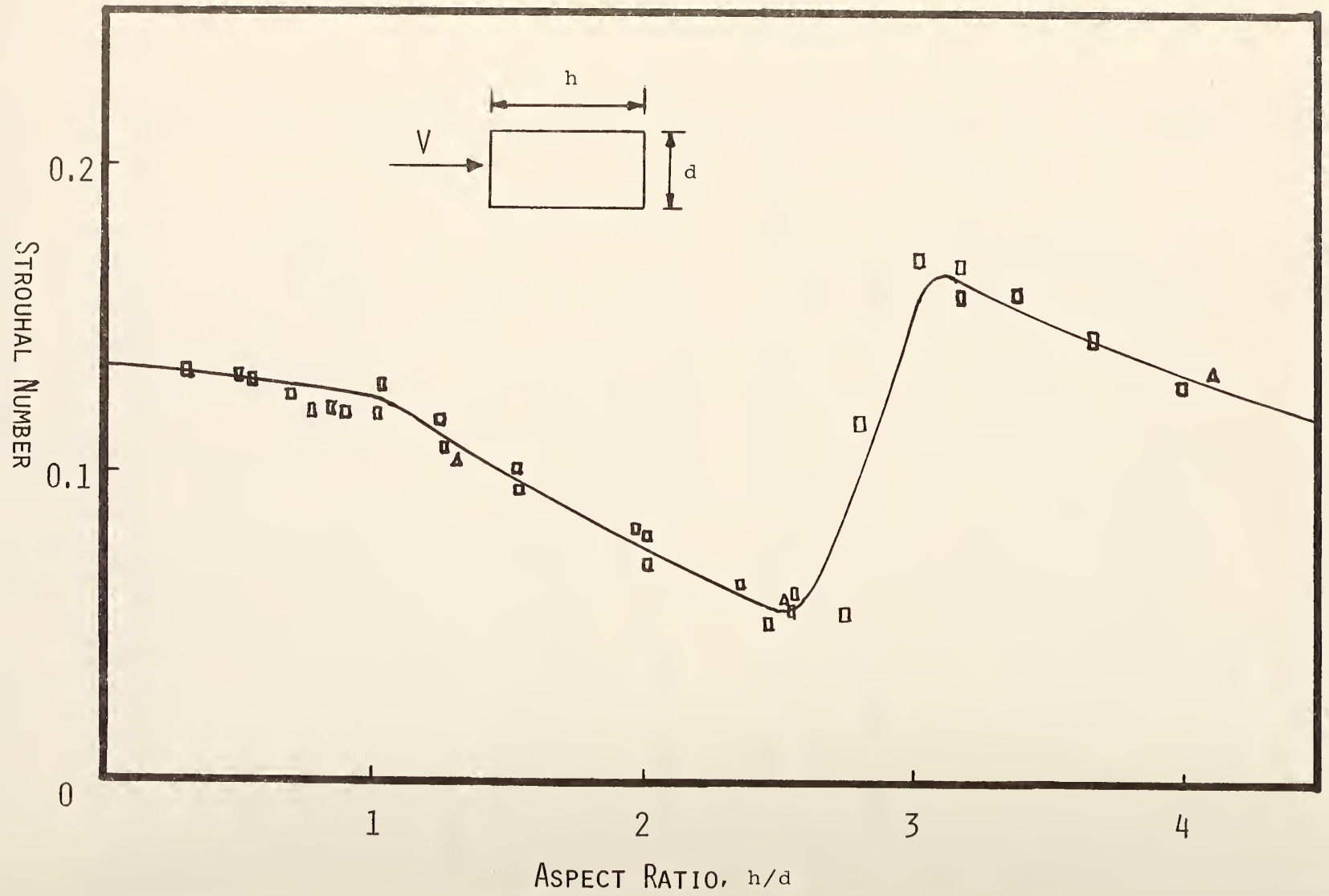


FIG.21. STROUHAL NUMBERS FOR RECTANGULAR CROSS-SECTIONS

except when h/d is in the range of 1.5 to 3 where Strouhal Number can be as low as 0.06.

3. Other Shapes

As the radius of the round corner in the rectangular section increases to a limit, the section becomes an ovaloid, which resembles an ellipse. Ovaloidal as well as elliptical sections have been investigated by a few researchers for a limited range of Reynolds numbers. The results are shown in Fig. 22. It is seen that the results are in general agreement with what might have been expected from the extrapolation from the results for rectangular sections. The supporting condition is not given but the rather high Strouhal Numbers in the transition range, seem to indicate that the specimens were probably held stationary during the tests. If the specimens were allowed to vibrate with the excitations, the dominating Strouhal Numbers should not differ much from those for subcritical in the transcritical range. Further experiments are needed to verify this conjecture.

Scattered results for other miscellaneous shapes of interest to aviation and space technology such as diamond, triangle, and crescent are available in the literature. The results will not be presented here, since they are rather incomplete and the sections themselves have limited applications to structural design. It is sufficient to say the Strouhal Number is generally in the range of 0.15 to 0.2 and increases gradually with the increase of Reynolds number up to the transition range. If the member is held stationary, the Strouhal

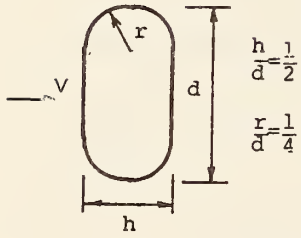
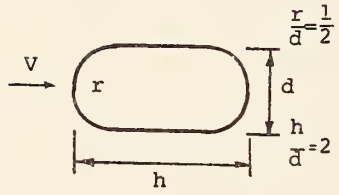
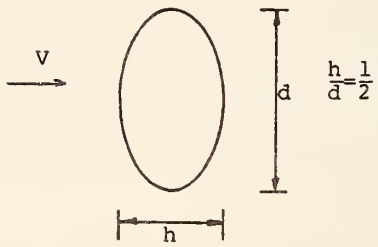
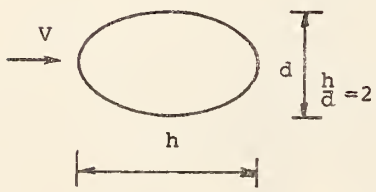
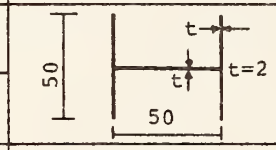
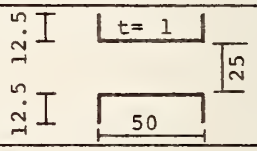
Section Shape	Strouhal Frequency $St = \frac{fd}{V}$	Applicable Range of Reynolds Number
	0.2 to 0.35	$6x10^5 > Re > 2x10^5$
	0.35	$1x10^6 > Re > 6x10^5$
	0.4	$2.5x10^6 > Re > 3x10^5$
	0.2	$7x10^5 > Re > 1x10^5$
	0.12	$5x10^5 > Re > 3x10^5$
	0.60	$2x10^6 > Re > 1x10^6$

FIG.22 STROUHAL NUMBERS OF OVALOIDS AND ELLIPSES

Number will exhibit a characteristic jump to around 0.4 to 0.6, similar to the case of cylinders and rectangular sections, where the Reynolds numbers fall in the transition zone. Otherwise, the cylinder will vibrate with excitations at the "correct" frequencies.

Of particular interest to the bridge designers are the structural rolled shapes, which includes HP, I, Channels, Angles, Wide-Flanges, and Built-Up-Sections. The best source of information on Strouhal Numbers for rolled shape is ASCE Task Force on Wind Force Committee Report, which contains a comprehensive table (Fig.23). It is seen that a variety of structural shapes and built-up sections are included. However, with the exception of the cylinder, no indication of Reynolds numbers is given. From the discussion in the previous section, all the structural shapes are sharp-cornered. Since the separation points of the shear layers must be fixed on the sharp corners, the dependence of Strouhal Numbers on the Reynolds numbers is probably not very strong.

The variation of Strouhal Number between different cross-sectional shapes (regardless the wind direction) is not very large. For example, among all the sections which possess two axes of symmetry, the Strouhal Number is a minimum for HP sections with a value of 0.12 and is maximum for twin channel sections with a value of 0.15. For unsymmetric sections, the Strouhal Number can vary between 0.114 to 0.168. The only other measurement known to us is by Narita for H shapes with depth/width ratios of 1/2 and 3/4. The reported Strouhal Numbers were 0.115 and 0.12, respectively. These are in reasonable agreement with data given in Fig. 23.

wind	profile dimensions in mm	St	wind	profile dimensions in mm	St
→		0.12	↓		0.147
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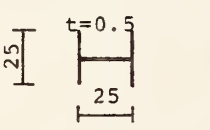
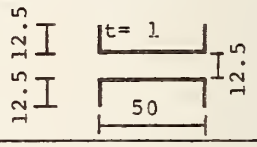
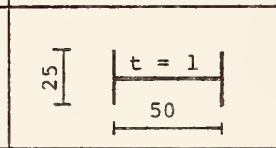
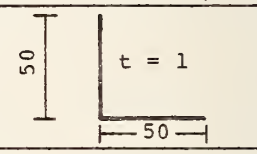
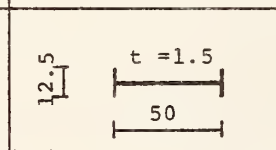
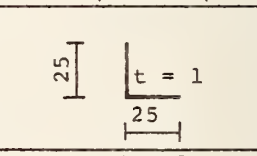
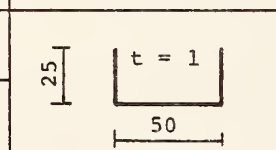
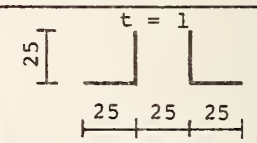
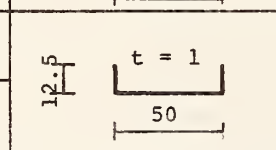
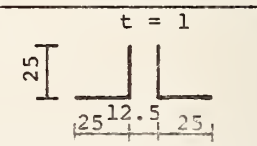
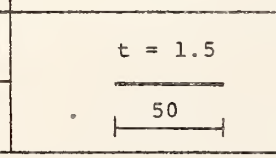
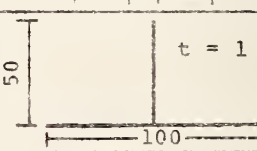
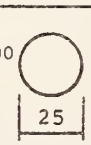
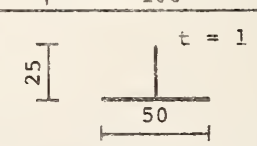
→		0.12	↓		0.15
↓		0.144	← ↑ ↙		0.145 0.142 0.147
↓		0.145	← ↑ ↙		0.131 0.134 0.137
↓ ↑		0.14 0.153	→ ↓		0.121 0.143
↓ ↑		0.145 0.168	→		0.135
→ ↓		0.156 0.145	→		0.160
Cylinder 11800<Re<19100 		0.200	→ ↑		0.114 0.145

FIG. 23 STROUHAL NUMBERS OF STRUCTURAL SHAPES

From the above discussion, it appears to be reasonable to estimate the Strouhal Number of HP sections to be 0.12 for engineering purposes. In view of the fact that the most useful range of Reynolds numbers should be in the transition range in which the excitation frequencies are broad-banded, a crude estimate of the Strouhal number should not lead to serious consequences.

On the other hand, it is regrettable, or even embarrassing, that members of great engineering application such as HP sections had not stimulated more than cursory attempts in the determination of their Strouhal frequencies. A more comprehensive program to determine the Strouhal Numbers of commonly used structural shapes should be a worthwhile undertaking.

4. Effect of Wind at an Oblique Direction

It is of great practical interests to determine the Strouhal Number when the wind direction is at an angle other than 90 degrees with the longitudinal axis of the circular cylinder. This type of investigation has become popular during the last decade. The range of yaw angles covered was very extensive but the range of Reynolds numbers is limited to below 2×10^4.

It is expected that the flow would have both longitudinal and transverse components. If the shear layer separation is unaffected by the presence of spanwise flow and the vortex street is undisturbed by the yaw angle, vortices will shed at a frequency corresponding to the normal velocity component, i.e.,

$$St_\alpha = St \sin\alpha$$

where α = angle between the flow and the longitudinal axis of the stationary cylinder. Observations seem to confirm this assumption. Similar results were observed for yawed music wire, which can freely respond to the excitation. When α is less than 18 degrees, there is some scatter of frequencies with more broad band width. Fig. 24 shows the comparison between the test results and the computed frequencies based on the Sine Law. It is seen that the agreement is rather good, at least for low Reynolds numbers. Very little is known about the yaw effect at high Reynolds numbers. There is no reason to expect that the results would be different from that for lower Reynolds numbers.

When the wind is applied at an angle of inclination to the width of the body, the effect depends on the length of the after-body as discussed before. The lift coefficient would be very sensitive to the angle of inclination. Also, the flow pattern may be very different and sometimes the galloping vibration is liable to occur at relatively high angle of inclination. This discussion, however, is beyond the scope of this report.

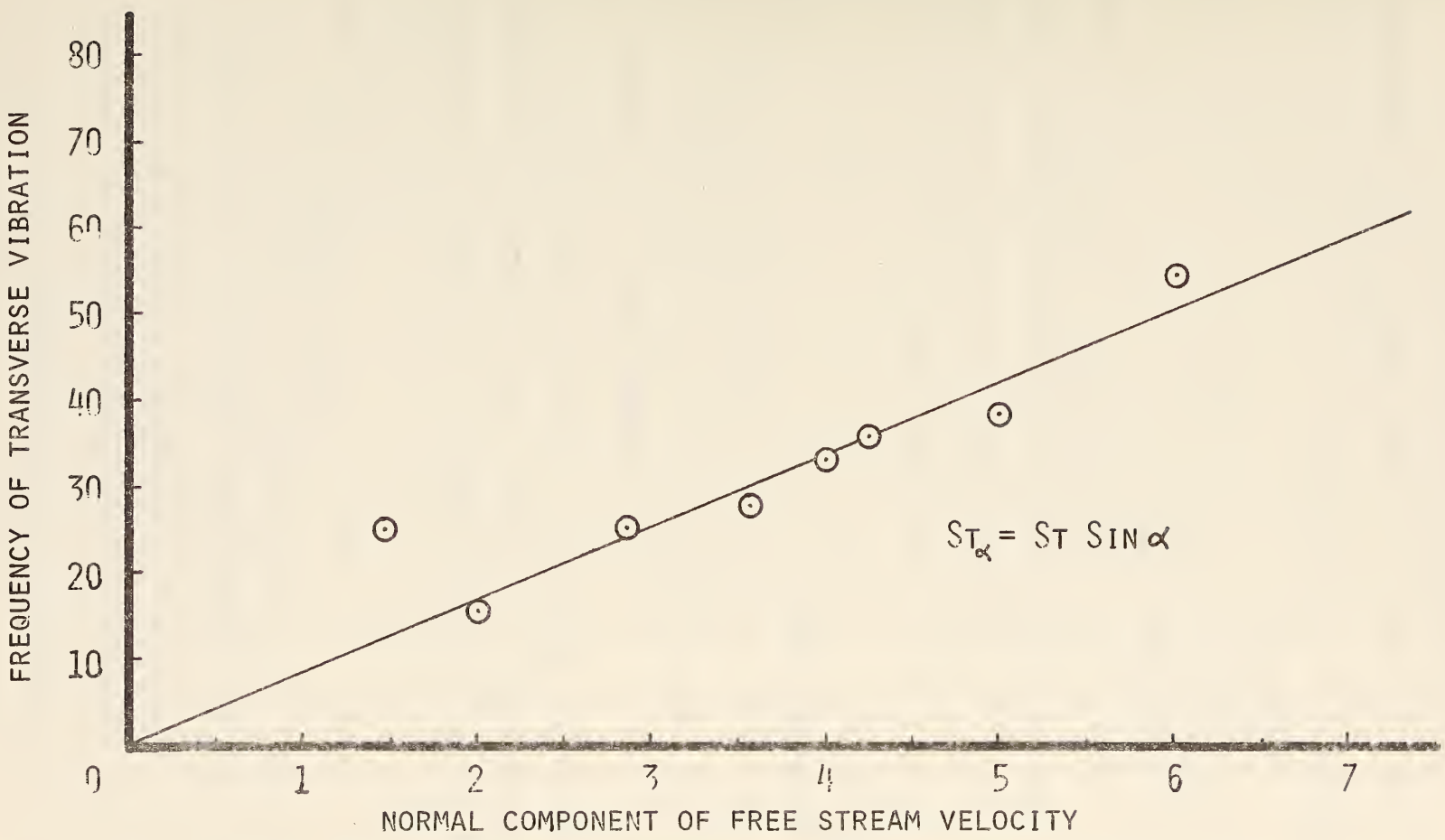


FIG. 24 SINE LAW GOVERNING STROUHAL NUMBER IN OBLIQUE FLOW

V. SUPPRESSION OF VORTEX SHEDDING

There are three basic methods to mitigate the vortex-induced vibrations:

(1) Aerodynamic

(2) Mechanical

(3) Analytical

All these methods have been used to varying degrees of success. Systematic procedure or devices have been derived from these basic methods and used in practical cases. The results were satisfactory or at least encouraging. The following sections will treat each method in detail.

1. Aerodynamic Method

The aerodynamic method of suppressing the vortex induced vibration entails the disruption of the vortex forming mechanism. From p.46 Chapter III it is stated that alternating shedding of vortices can occur only in a bluff body in which the boundary layers can separate to free shear layers. To have a strong vortex street, the separation points must be lined up, preferably in a straight line perpendicular to the current direction, so that a spanwise coherence is effected. Furthermore, the shear layer must have an adequate vortex formation length to roll up. The area behind the bluff body must be maintained as a fluctuating but essentially low pressure region. If any or all of these conditions are disrupted, the vortex-shedding vibration will be greatly attenuated or even stopped altogether.

The following devices were designed for the purpose of disrupting some of these conditions:

A. Streamlined Fairings, which change the bluff bodies into streamlined bodies.

B. Roshko's Splitter Plate or Baird's Saw-Toothed Paneling, which interferes with the fluctuation of the localized low pressure region in the aft of the cylinder.

C. Perforations in the Bluff Body, which eliminate the low pressure region in the aft by means of base bleeding.

D. Perforated shroud over the Bluff Body, which interferes with both the separation of shear layer and the low pressure region.

E. Trailing Ribbons which interfere with the shear layers in the vortex formation length.

F. Helical Strakes or Spiral Wrapping which disrupt the spanwise coherence of vortex shedding.

The design of these devices is at present beyond the capability of analytical means and must be done by trial and error method in a wind tunnel. The following paragraphs summarized the main results and design criteria.

(A) Streamlined Fairing

The streamlined fairings have been in widespread usage for many years and considerable research effort has been directed to assess their hydrodynamic performance. In general, a properly designed fairing can be effective as long as the wind direction remains unchanged. Also, the long 'afterbody' produced by a well-proportioned fairing is amenable to galloping.

(B) Splitter Plate

A splitter plate is a thin partition placed along the centerline of the wake downstream of a cylinder. It appears that it causes the two shear layers, in the formation length, to be isolated from each other and broken down independently. It also has the effect of increasing the back pressure and thus reducing the pressure gradient from the separation points to the wake. The indirect result is a reduction of drag coefficient of the cylinder. In the subcritical region of Reynolds numbers, the splitter plate forces the vortices to form further downstream along its length. This downstream shift of formation position is accompanied by a decrease of the Strouhal frequency. The effective length of the splitter plate was found to be about 4 to 5 cylinder diameters. Limited tests on splitter plate for supercritical range indicated that the effectiveness was much less noticeable. The splitter plates are most effective near antinodes of a vibrating flexible cable. For economic reasons, the splitter plates need not be continuous along the entire length of the cylinder, but rather, they can be placed intermittently along the length, each segment being about 10 to 20 diameters long. Also, Baird found that segment of plates of varying widths, say triangular shaped, (a bank of the plates would have an appearance of saw teeth) were more effective than those of constant width. Alexander found that random arrangement of longitudinal fins was also an effective design.

(C) Perforations

Perforations (Fig. 25) are holes of suitable sizes and shapes on the bluff body, which allow a sufficient amount of additional fluid directly into the localized low pressure region in the aft. It was found that porosity of 0.5 was effective in inhibiting the vortex shedding. The size, shape and distribution of the holes are apparently unimportant in the performance of porosity, only the total hole area relative to the total frontal area matters. For economical reasons, it is easier to provide a few large holes than a large number of small holes. Also, the curvature of the hole boundary should be as flat as possible to minimize the effect of stress concentration. It appears that the ovaloidal holes equally spaced on the surface through the body would be a good choice. This arrangement has been used very effectively in the box members in trussed bridges for weight reduction purposes. The same design can be used also for vibration suppression.

(D) Shroud

Shroud is a perforated cylindrical shell enclosing the bluff body with a small diameter gap,(Fig. 26). It is found that the amount of perforation relative to the total area should be about 20 to 30 percent and the gap should be about 0.12 times the diameter. This method has been successfully applied to anti-corrosion anodes of cooling water ducts, multi-flue chimney stacks, and square-section towers.

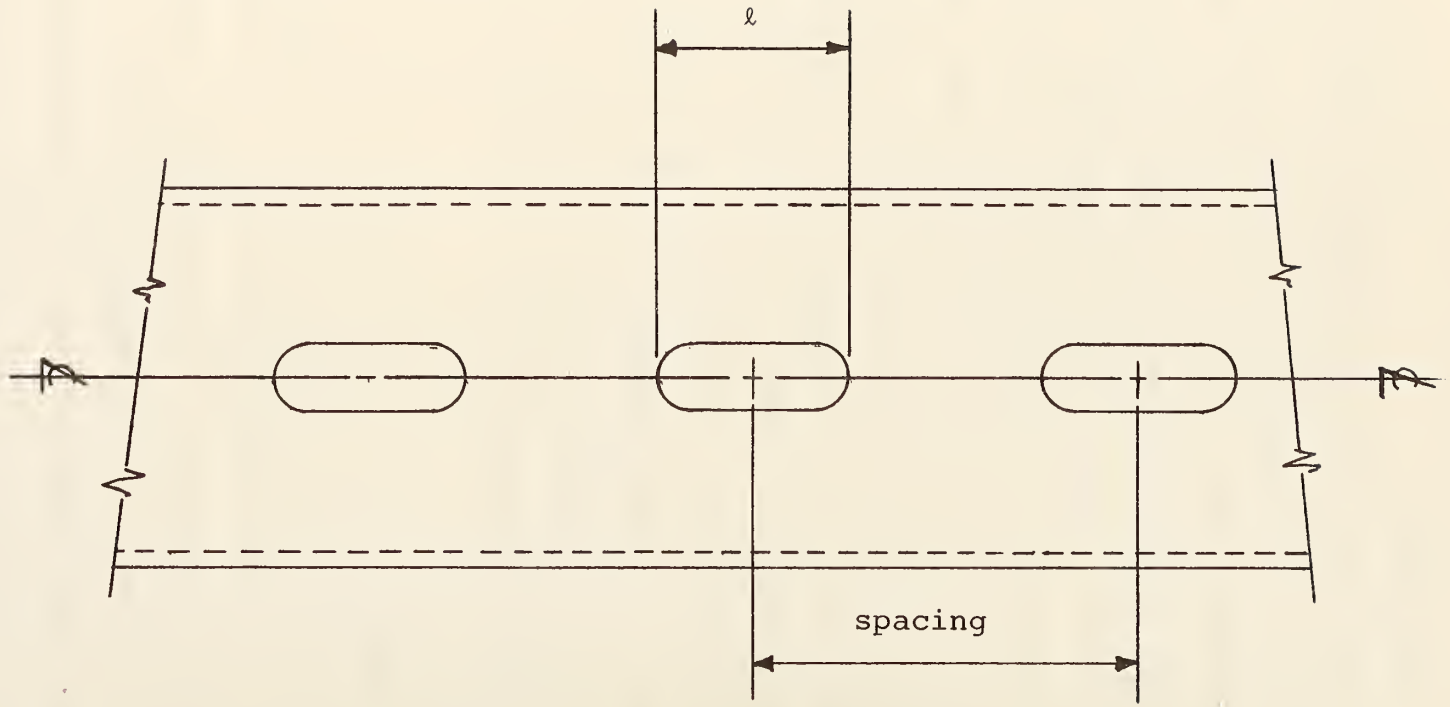


FIG. 25 TYPICAL WEB PERFORATION IN A BOX BEAM

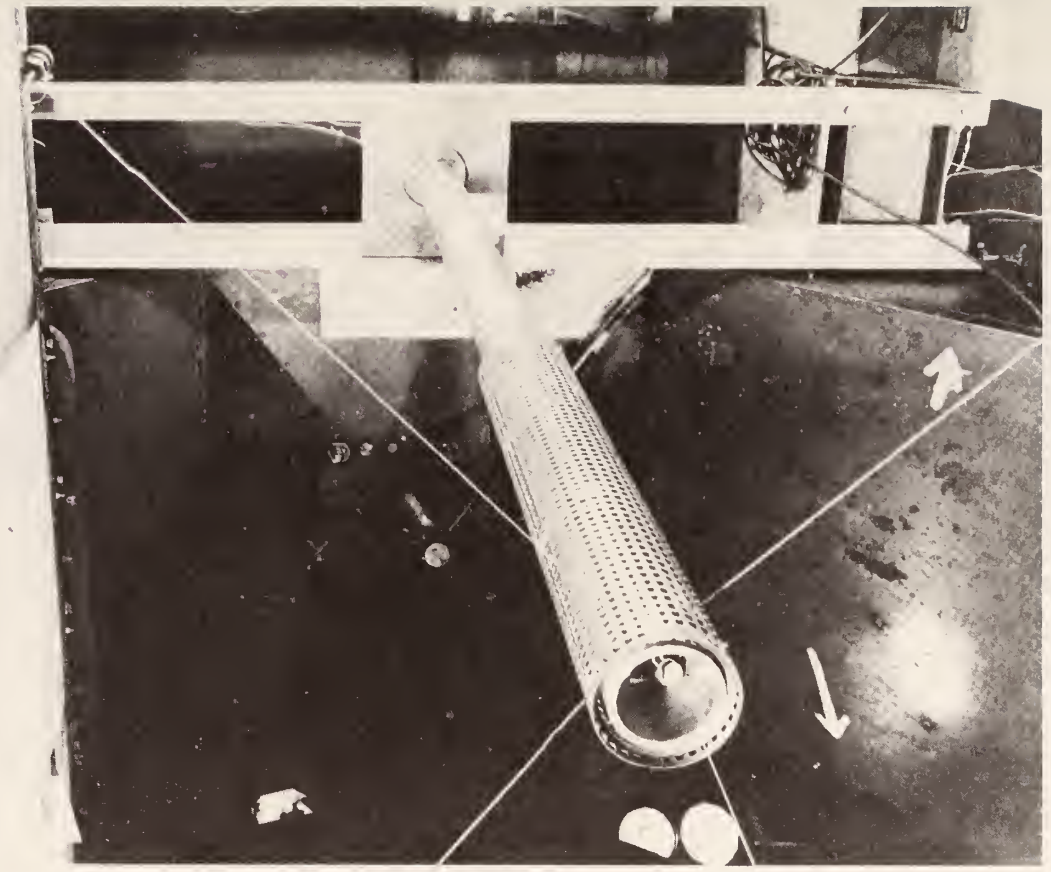


FIG. 26 SHROUD AS A VIBRATION SUPPRESSOR

(E) Trailing Ribbon

Trailing ribbons are thin plastic film strips attached to the bluff body so that they flutter in the vortex forming length downstream from the bluff body. The fluttering motions of the ribbons interfere with the rolling up of the shear layers to prevent them from forming a vortex street. It has been used successfully in marine applications, to suppress the strumming of a towed array. It was found there that well-designed ribbons reduced both the frequency and the amplitude of vibration, at least in water,for Reynolds numbers in the subcritical range. It is presumed that similar effect could also be realized for a bluff body in wind. The optimum ribbon configuration was found to be 6 and 10 d long*, by 2 d wide spaced 1 and 2 d apart. In an oblique stream, the ribbons have a tendency to lay flat along the longitudinal axis of the cylinder if any appreciable spanwise stream flow is present. In such circumstances the effectiveness of the trailing ribbons would be greatly impaired.

(F) Helical Strakes

Helical strakes (Fig. 27) are ridges wrapped around a cylindrical or nearly cylindrical body to trip the separation points on the cylinder. Due to the helical pattern of the strakes, the separation points would be expected to vary along the axis of the cylinder. The vortex shedding would become incoherent spanwise and

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* "d" denotes the diameter of the cable

FIG. 27 HELICAL STRAKES AS VIBRATION SUPPRESSOR

the fluctuating lift force thus would be greatly weakened. Many factors affect the performance of the strakes, which are: height, width, and shape of the strakes, and the pitch of the helical winding. Tests by Scruton, Woodgate, Fabula and others show no conclusive results. It is generally agreed, however, that the ridge height should be 0.1 d or more to be effective.

2. Mechanical Method

There are two main types of devices to minimize vibrations mechanically: Tie-downs and Damping. Tie-downs are struts which connect the expected anti-nodes of the member to some rigid supports. The amount of force taken by the strut is dependent on the aerodynamic lift force of the member, which is usually rather small in terms of structural strength.

Dampers are a mass-spring combination which has same natural frequencies as one of the natural frequences of the structure itself. The energy is transferred from the structure to the damper, and is dissipated by friction with viscoelastic pads, synthetic rubber stemmed damper, etc. Spring can be leaf, helical, or torsion types, and the position of the weight is adjustable. The damper usually needs frequent maintenance and is not very effective. A Stockbridge damper (Fig. 28) consists of a double cantilever attached to a vibrating structure. The cantilever is tuned to vibrate with the same frequency as the vortex shedding frequency but is π-radians out of phase. The inertial force is therefore cancelled out this way. It is not a true damper in the ordinary sense. It is generally used for

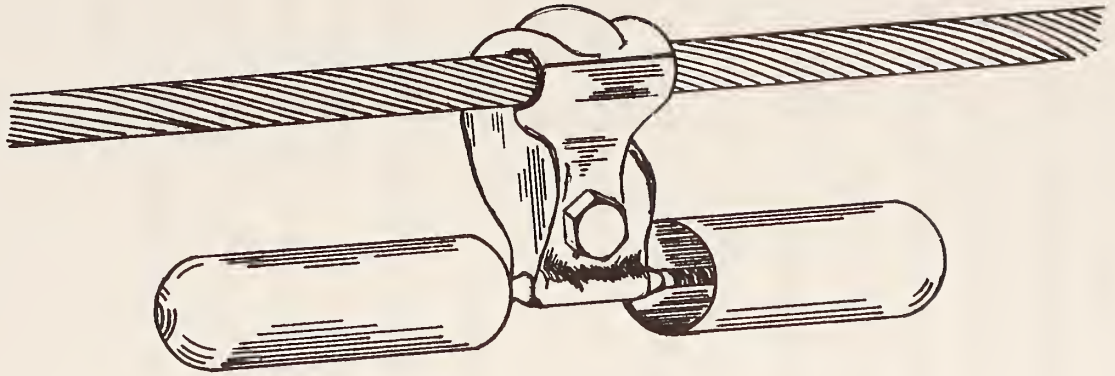


FIG. 28 STOCKBRIDGE TUNEABLE DAMPER

light structures such as a wire but the same principle can be used for very heavy structures, even to restrain a ship from excessive rolling.

3. Analytical Method

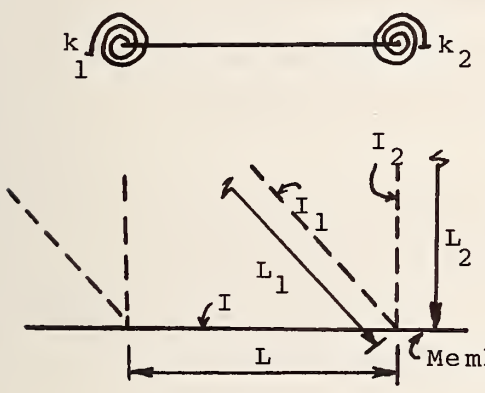
It is recommended by some that the violent vibration due to resonance can be designed out by setting the natural frequency corresponding to a wind velocity much above the prevailing wind velocity near the site of the structure. This is not always possible and is very wasteful even if it is possible.

A more practical idea is to design the member such that the Reynolds numbers corresponding to the prevailing wind speeds be kept within the supercritical regime (random shedding range, Fig. 17). We recall that the excitation frequency within the transition zone is broad-banded, (Figs, 19 & 20). It is clear then that the dominating frequency would carry a relatively small share of total energy of the wind. In such cases, the excursion and bending moment are expected to be relatively small (see example 5, Part C, Chapter III). The analytical method can be a very useful tool when it is used in conjunction with some or all of the other methods.

VI. DESIGN DATA

(1) End - Fixity Coefficients

In the determination of the natural frequencies and mode shapes of a bridge member, it is necessary to know the degree of fixity of that member at its ends. This can be accomplished easily as follows: The member should be considered supported at each end by springs which represent the action of the surrounding members (See Fig. below.) If the spring constant k can be determined for each spring, then the degree of fixity can be determined. From the standard theory of structures it is known that, for a unit moment imposed on an end of the member, the angle of rotation that results in the member at that end is given by:



$$\theta = \frac{n}{4E \sum_i \frac{I_i}{L_i}}$$

where $\sum_i \frac{I_i}{L_i}$ equals the summation of the stiffness of adjacent members of the particular joint containing the end of the member being analyzed n is a constant which depends on the continuity of the member in consideration relative to the joint. If the member is continuous through the joint (e.g. member A) then n = 2; this is commonly the case for a lower chord in a truss. If the member is terminated at the joint (e.g., member B) then n = 1; this is commonly the case for a hanger of a bridge deck.

The spring constant at an end of a member is then

$$k = \frac{1}{\theta} = \frac{4E}{n} \sum_i \frac{I_i}{L_i}$$

and the nondimensional spring constant, namely, the "end fixity condition" is

$$\sigma = \frac{kL}{EI} = \frac{4}{n} \frac{\sum_i \frac{I_i}{L_i}}{\frac{I}{L}}$$

where L = Length of the member in consideration,

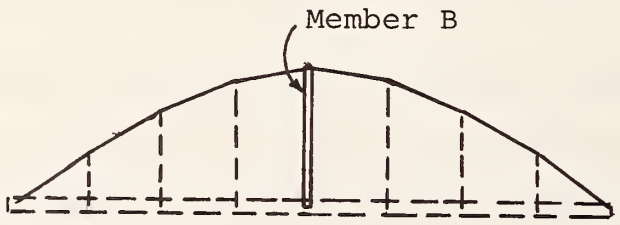
I = Moment of inertia of the member in consideration.

Specifically, from the definition of n stated above, the end-fixity conclusions are

$$\sigma = \frac{4 \sum_i I_i/L_i}{I/L} \qquad \text{for hangers (member B)}$$

$$\sigma = \frac{2 \sum_i I_i/L_i}{I/L} \qquad \text{for lower chord (member A)}$$

The above expressions show that the end-fixity condition σ has the following physical interpretation: it is equal to four times the ratio of the joint stiffness and the flexural stiffness of the member in question.



(2) Damping Coefficients

The damping in a bridge member is due to a combination of structural (material), viscous and aerodynamic effects. The damping coefficient is usually expressed in the logarithmic decrement, which varies with amplitude, mode (flexural or torsion) and material. For members which have considerable flexural strength, such as a structural shape or a built-up section, the aerodynamic damping is negligible and the damping is primarily due to structural damping at low excursions and due to viscous damping at high amplitudes.

Whitebread suggested values of logarithmic decrement for various types of construction:

Type of Construction	Logarithmic Decrement
Lightweight aluminum	0.005 to 0.01
Welded steel (unlined)	0.01 to 0.05
Welded steel (lined)	0.03 to 0.07
Concrete (in situ)	0.05 to 0.10
Concrete (precast)	0.07 to 0.15

Narita reported some experimental damping factors for three steel bridges in Japan, and one in the U.S.S.R. The logarithmic decrement values for the hangers range from 0.008 to 0.032 for built-up plates and from 0.07 to 0.014 for pipes.

Selberg reported that the logarithmic decrement for steel bridges ranges from 0.02 to 0.05.

Sachs reported that the logarithmic decrement for cables is about 0.002 which is much lower than built-up section and the pipe. Table 2 shows damping coefficients of chimneys, towers, etc., appeared in literature.

Table 2 : Damping and Frequency Characteristics of Typical Structures

Structure	Mode of excitation	Location	Material	Tip dia., ft-in.	Height, ft	Maximum amplitude, in.	δ	f, c/s
Chimney stack		Japan	Steel, unlined				0.06	
" "		"	Steel, Gunite lined					
" "		"	" " "				0.09	
" "	Cable release	Moss Landing, U.S.A.	" " "	11-4	225		0.05 0.04	0.82(0.85)*
" "	" "	"	" " "	"	"	4	0.07	" "
" "	" "	"	Steel, unlined	"	"		0.02	1.12(1.23)
" "	" "	"	" "	"	"	3	0.07	" "
" "	" "	Contra Costa, U.S.A.	Welded steel, unlined	11-0	200	small	0.04	0.97(1.06)
" "	" "	" " "	Welded steel, Gunite lined	"	"	"	0.06	0.71(0.75)
" "	" "	Chiba, Japan	" " " "	14-6	300	2	0.03	0.67
" "	" "	Conner's Creek, U.S.A.	Riveted steel, Brick lined			½-1½	0.04	
" "	" "	St. Clair, U.S.A.	Welded steel, Gunite lined			1-3	0.06	
" "	" "	Aldermaston, G.B.	Welded steel, unlined	4-0	150		0.01	0.92
" "	Whirling arm	Newman Spinney, G.B.	Lightweight R.C.			small	0.08	1.47
" "	" "	" " "	" "			0.3	0.12	1.41
" "	Rockets	Ferrybridge "B" Power Station, G.B.	"R.C."	24-0	415	0.56	0.06	0.61
Television tower	Cable	Crystal Palace, G.B. (Complete to 440 ft)	Bolted steel		440	1½	0.02	

Table 2: Damping and Frequency Characteristics of Typical Structures (con't)

Structure	Mode of excitation	Location	Material	Tip dia., ft-in.	Height, ft	Maximum amplitude, in.	δ	f, c/s
Television tower	Rockets	Crystal Palace, G.B.(complete to 710 ft)	Bolted steel		710	8	0.18	0.30(0.34)
Chimney stack	cable	Grimsby,G.B.	Welded Steel, unlined	7-0	250		0.05	1.3
" "	"	Mizushima, Japan	" " "	17-6	296		0.03	0.75
" "	"	Wakayama, Japan	" " "	13-6	274		0.038	1.15
" "	"	Sakai,Japan	" " "	12-9	253		0.032	0.69
Tubular tower	"	Bienne-Triage, Switzerland	Bolted aluminium	2-3	124		0.10	0.75
Guyed cylindrical mast		Rimouski, Canada	Welded steel	7-4	120		0.05	2.1
" " "		Halifax, Canada	" "	7-4	500		0.05	0.31

* Figures in parentheses show calculated frequencies

(3) Lift Coefficients

Since Lord Rayleigh observed that the vortex-shedding vibrations were affected in a plane perpendicular to the stream flow, it follows that there must exist a fluctuating lift force on the specimen. Early attempts to measure this lift force were made by Schwabe, Bingham and others. Many of these early experiments were handicapped by inadequate instrumentation and poor test procedure. Their results are widely scattered and must be treated with caution.

The first controlled, systematic measurement of lift acting on a cylinder at high Reynolds numbers were carried out by Fung in 1960. The tests were duplicated by Schmidt four years later. The rms lift coefficients from these sources are shown in Fig. 29. It is seen that one is nearly three times as high as the other. Schmidt attributed the difference to the fact that Fung's model had minor surface irregularities while his was highly polished. Keefe also found that gap, vents and tip shapes at the ends of the cylinder had a tendency to increase the unsteady lift force. Even a trip wire or a thin tape bonded longitudinally on the cylinder would do the same. It appears that the lift force is affected by the spanwise coherence of the shedding mechanism. In fact, the lift coefficient is also closely related to the drag, pressure and Strouhal number. Since the Strouhal number in post-critical regime is strongly affected by the movement of the cylinder, the lift coefficient must be also.

FIG. 29 FLUCTUATING LIFT COEFFICIENTS

The relation between the rms and peak lift coefficients are shown in Fig. 30, as reported by Fung. It is seen that the peak lift is about twice of the rms value.

In the limited literature available the lift coefficient C_L was reported by Narita who estimated it to be approximately 1.15 for 3 different types of H shapes.

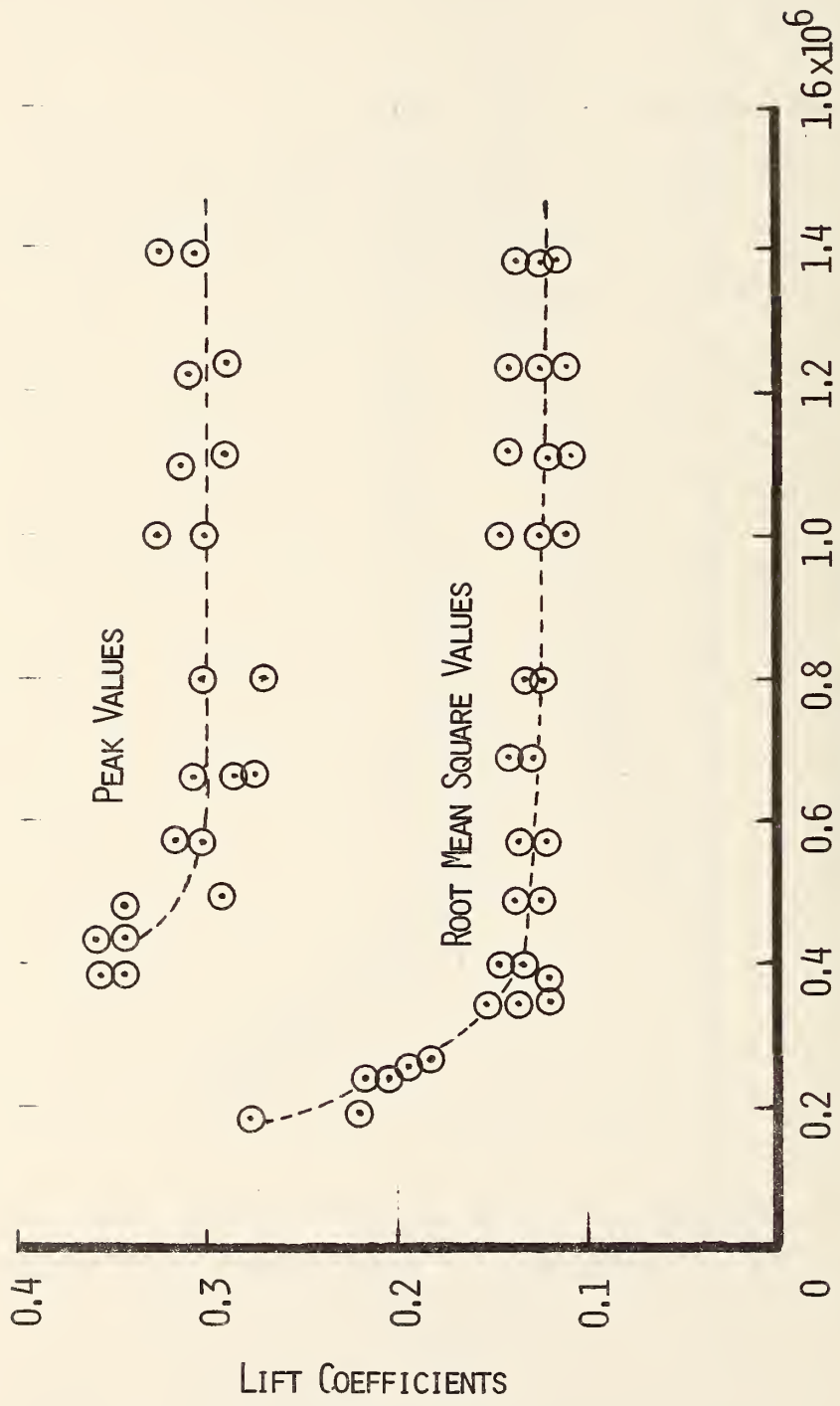


FIG. 30 PEAK AND RMS LIFT COEFFICIENTS

PART B

MATHEMATICAL THEORY

I. NATURAL FREQUENCY AND NORMAL MODES

(1) Flexural Vibrations

The small amplitude, free, transverse vibration of a beam is governed by

$$\frac{d}{dX^2}\left(EI\ \frac{d^2Y}{dX^2}\right) - \rho A\ \omega^2 Y = 0$$

where Y = transverse displacement

EI = flexural rigidity

ρ = mass density

A = cross-sectional area

ω = circular frequency.

If axial tension T is imposed, the equation becomes

$$\frac{d^2}{dX^2}\left(EI\ \frac{d^2Y}{dX^2}\right) - T\ \frac{d^2Y}{dX^2} - \rho A\omega^2 Y = 0 \quad \text{.....(1)}$$

For prismatic beams, EI = constant. Nondimentionalizing Eq.(1) by setting

$$y = \frac{Y}{L}, \qquad x = \frac{X}{L}$$

and dividing through by EI/L^3 (where L = length of the beam), we obtain,

$$\frac{d^4y}{dx^4} - P\ \frac{d^2y}{dx^2} - Q\ y = 0$$

where $P = TL^2/EI$ = nondimensional force

$Q = \rho A\omega^2\ L^4/EI$ = nondimensional frequency.

By standard methods, we obtain a general solution

$$y = C_1 \mathrm{Sinh}\alpha x + C_2 \mathrm{Cosh}\alpha x + C_3 \mathrm{Sin}\beta x + C_4 \mathrm{Cos}\beta x \quad \text{.....(2)}$$

$$\alpha^2 = \sqrt{\frac{P^2}{4} + Q} + \frac{P}{2} \quad \text{.....(3)}$$

$$\beta^2 = \sqrt{\frac{P^2}{4} + Q} - \frac{P}{2}$$

Constants, C_1, C_2, C_3, and C_4, in Equation (2) can be evaluated for fixed-fixed, free-free, fixed-simple, simple-simple, and other beam end support conditions. For the most general case, i.e., elastically constrained ends condition, no results are found in the references. This case, however, is the most important for bridge members, and we shall evaluate the constants for this case presently.

The boundary conditions are

$$y(0) = y(1) = 0$$

$$\frac{d^2y}{dx^2} - \sigma_1 \frac{dy}{dx} = 0 \qquad \text{at } x = 0$$

$$\frac{d^2y}{dx^2} + \sigma_2 \frac{dy}{dx} = 0 \qquad \text{at } x = 1 \qquad \text{.....(4)}$$

where $\sigma_1 = \frac{k_1 L}{EI}$, $\sigma_2 = \frac{k_2 L}{EI}$ and k_1, k_2 are respective torsional moduli at the ends of the beam. By applying the four conditions in Eq.(4) to Eq. (2), the vanishing coefficient determinant yields

$$\{(\alpha^2 + \beta^2)^2 + \sigma_1\sigma_2 (\alpha^2 - \beta^2)\} \text{ Sinh}\alpha \text{ Sin}\beta - 2\sigma_1\sigma_2\alpha\beta$$

$$(\text{Cosh}\alpha \text{ Cos}\beta - 1) + (\sigma_1 + \sigma_2)(\alpha^2 + \beta^2)\{\alpha\text{Cosh}\alpha \text{ Sin}\beta -$$

$$\beta\text{Sinh}\alpha \text{ Cos}\beta\} = 0 \qquad \text{.....(5)}$$

Equation (5) is the most general frequency equation for small amplitude transverse vibration of an Euler-Bernoulli

beam. As far as we know, it has never appeared in literature. We can show that it includes all existing results as special cases.

After the natural frequencies are evaluated from Eq.(5), we can substitute the results back into Eq.(4) to obtain the relationship between the constants of integration. By arbitrarily setting $C_2 = 1$ and knowing $C_4 = -C_2$ we can determine uniquely C_1 and C_3. Finally, we obtain the mode shape as follows: (subscript n omitted)

$$w(x) = K_1 \text{Sinh}\,\alpha x + K_2 (\text{Cosh}\,\alpha x - \text{Cos}\,\beta x) + K_3 \text{Sin}\,\beta x \quad \ldots(6)$$

where

$$K_1 = \begin{vmatrix} \alpha^2 + \beta^2 & \sigma_1\beta \\ -(\alpha^2\text{Cosh}\alpha + \beta^2\text{Cos}\beta) & -\beta^2\text{Sin}\beta + \sigma_2\beta\text{Cos}\,\beta \\ -\sigma_2(\alpha\text{Sinh}\alpha + \beta\text{Sin}\beta) & \end{vmatrix}$$

$$K_2 = \begin{vmatrix} \sigma_1\alpha & \sigma_1\beta \\ \alpha^2\text{Sinh}\alpha + \sigma_2\alpha\text{Cosh}\alpha & -\beta^2\text{Sin}\beta + \sigma_2\beta\text{Cos}\,\beta \end{vmatrix}$$

$$K_3 = \begin{vmatrix} \sigma_1\alpha & \alpha^2 + \beta^2 \\ \alpha^2\text{Sinh}\alpha + \sigma_2\alpha\text{Cosh}\alpha & -(\alpha^2\text{Cosh}\alpha + \beta^2\text{Cos}\beta) \\ & -\sigma_2(\alpha\text{Sinh}\alpha + \beta\text{Sin}\beta) \end{vmatrix}$$

Equation (6) is the most general modal shape expression in the framwork of Euler-Bernoulli theory. Several degenerated cases are interesting. For example:

For a beam with simple supports at each end,

$$\sigma_1 = \sigma_2 = 0$$

so Eq. (5) becomes

$$(\alpha^2+\beta^2)^2 \, \mathrm{Sinh}\alpha \, \mathrm{Sin}\beta = 0$$

which means $\mathrm{Sin}\beta = 0$; since $\mathrm{Sinh}\alpha \neq 0$
therefore $\beta = n\pi$.

The associated mode shape is $w = \mathrm{Sin}\beta x$.

For the case of a beam with a simple support at one end and a fixed support at the other end,

$$\sigma_1 = 0 , \qquad \sigma_2 \to \infty$$

so Eq. (5) becomes,

$$\frac{\alpha}{\beta} \tan\beta = \tanh\alpha$$

The associated mode shape is $w = \beta\mathrm{Cos}\beta \, \mathrm{Sinh}\alpha x - \alpha\mathrm{Cosh}\alpha\mathrm{Sin}\beta x$

For a beam with both ends fixed,

$$\sigma_1 \& \sigma_2 \to \infty$$

so Eq. (5) becomes,

$$\mathrm{Sinh}\alpha\mathrm{Sin}\beta - \frac{\alpha\,\beta}{(\alpha^2-\beta^2)} (\mathrm{Cosh}\alpha\mathrm{Cos}\beta - 1) = 0.$$

The associated mode shape is

$$w(x) = (\alpha\mathrm{Sinh}\alpha + \beta\mathrm{Sin}\beta)\cdot(\beta\mathrm{Sinh}\alpha x - \alpha\mathrm{Sin}\beta x) - \alpha\beta(\mathrm{Cosh}\alpha - \mathrm{Cos}\beta)\cdot (\mathrm{Cosh}\alpha x - \mathrm{Cos}\beta x).$$

Finally, for a beam simply-supported on one end and partially fixed on the other, the frequency equation becomes,

$$(\alpha^2 + \beta^2) \text{Sinh}\alpha \text{ Sin}\beta + \sigma_2 \{\alpha \text{Cosh}\alpha \text{ Sin}\beta - \beta \text{Sinh}\alpha \text{ Cos}\beta\} = 0$$

and the corresponding mode shape is

$$w = (\sigma_2 \beta \text{Cos}\beta - \beta^2 \text{Sin}\beta) \text{ Sinh}\alpha x - (\alpha^2 \text{Sinh}\alpha + \sigma_2 \alpha \text{Cosh}\alpha) \text{Sin}\beta x$$

we have computed numerical results of Eq.(5) to cover all possible conditions of beam end support, for cases where $\sigma_1 \neq \sigma_2$ and for the cases of applied tension. The results are shown in Appendix B.

(2) Torsional Vibrations

Non-uniform torsional vibrations of a thin, open section are governed by

$$EC_w \frac{d^4\Phi}{dX^4} - GC \frac{d^2\Phi}{dX^2} + \rho I_p \omega^2 \Phi = 0$$

where EC_w = warping rigidity

GC = torsional rigidity

I_p = polar moment of inertia

Φ = angle of twist per unit length.

To take care of axial tension a term

$$- \frac{T}{A} I_p \frac{d^2\Phi}{dX^2}$$

must be added to the equation.

To non-dimensionalize it, we set $\phi = \frac{\Phi}{L}$ $x = \frac{X}{L}$

$$\frac{d^4\phi}{dx^4} - P_1 \frac{d^2\phi}{dx^2} - Q_1 = 0$$

where $P_1 = (GC + TI_p/A)L^2/EC_w$

$$Q_1 = \rho I_p \omega^2 L^4/EC_w .$$

The general solution is again of the form of Eq.(4) except that, in this case,

$$\alpha^2 = \sqrt{\frac{P_1^2}{4} + Q_1} + \frac{P_1}{2} \qquad \text{.....(7)}$$

$$\beta^2 = \sqrt{\frac{P_1^2}{4} + Q_1} - \frac{P_1}{2} .$$

By this redefinition, the results for transverse vibration can be re-interpreted to apply also to the corresponding cases for torsional vibrations. It should be noted that, a simply supported end in torsion means no restriction to warping of cross-section at that end while a fixed end, full-restriction to warping. In either case, the angle of twist is zero.

Some contemporary bridges employ HP sections as slender members, which can only undergo nonuniform torsion as long as the joints remain unyielding against twisting. Others employ Box Sections which can resist no warping and wherein the uniform torsion prevails.

It is interesting to compare the effect of warping on the natural frequency of a HP beam in torsional vibrations. For sake of comparison, we consider simply supported beams. Solving for ω in Eq. (7)

$$\omega^2 = \frac{n^4\pi^4 EC_w}{\rho I_p L^4} + \frac{n^2\pi^2 (GC + \frac{TI_p}{A})}{\rho I_p L^2}$$

in which β is already substituted by $n\pi$. Calculation shows that for T = 0, the fundamental natural frequencies of a typical HP section can possibly be raised as much as 20% due to warping.

For thin closed sections, $EC_w = 0$, and the differential equation is reduced to a second-order one. Strictly speaking, EC_w is not zero, but is very small, so that the equation is a singular fourth order one, which requires a singular perturbation solution. For our purpose, we can ignore the "boundary layer effect" and treat it as a second order equation. It can be solved in a straight forward manner, but we omit it here, since it is much simpler to degenerate the frequency equation. See Part C , Chapter II for details.

II. RESPONSES IN SUBCRITICAL FLOW

(1) Hartlen-Currie Model

The response of an elastic beam to wind-induced excitation should be determined by the fluid-structure interaction analysis which involves the integration of Navier-Stokes equation and matching of pressure and displacement interfaces. A complete analysis is beyond the state-of-the-art or rather, if it could be done at all, the expenditure for computer usage would be prohibitive for the present purpose. Therefore, it is expedient to resort to a phenomenological approach as described below.

In the Strouhal range, the amplitude of oscillation of an elastic beam is nil in a non-resonant condition; even in a resonant condition, i.e., the Strouhal frequency is close to one of the natural frequencies of the beam, the amplitude remains quite small, on the order of ten percent of the dimension 'd' of the beam. For simplicity, we shall neglect the variation of the response of the beam along its longitudinal axis; a segment of the beam is allowed to move as a rigid body in response to the oscillating lift force. The elasticity effect is represented by springs at its ends.

Now consider an elastically-supported, viscously-damped, rigid dxd H-beam of length L (Fig.31) exposed to a flow of free-stream velocity V. The beam of total mass m is elastically-supported on springs of stiffness K and the viscous* damping co-

* Hysteretic or structural damping introduces only minor changes of small magnitude.

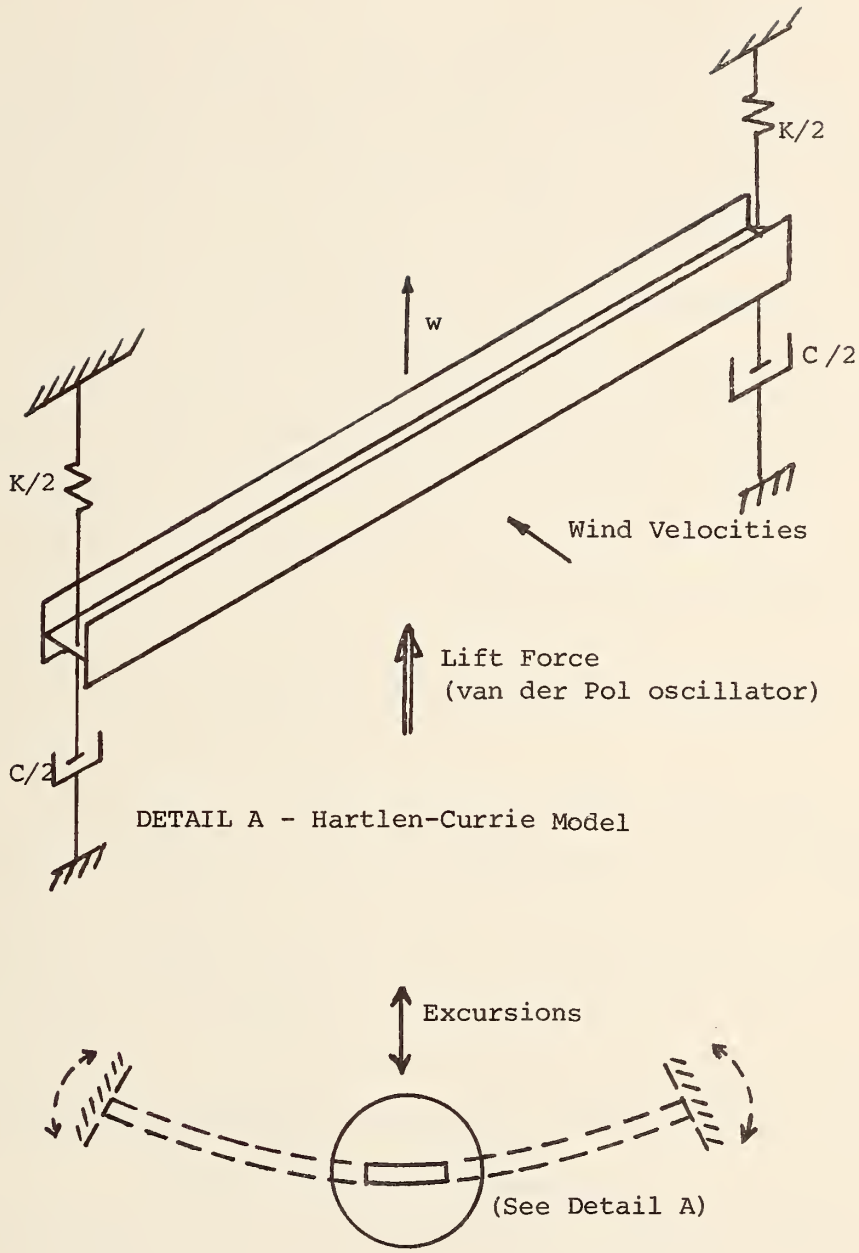


FIG. 31 VIBRATING BEAM MODELLED BY HARTLEN-CURRIE LUMPED MASS THEORY

.efficient C. The equation of motion of the beam is given by

$$m\ddot{w}(t) + C\dot{w}(t) + K w(t) = F(t) \quad \ldots\ldots\ldots(1)$$

where the dot over the displacement, w, indicates a derivative with respect to time and F denotes the external lift force acting on the beam given by

$$F(t) = \tfrac{1}{2} \rho_a V^2 dL C_L \quad \ldots\ldots\ldots\ldots\ldots(2)$$

wherein C_L denotes a time-dependent lift coefficient and ρ_a is the mass density of air.

For ease of subsequent manipulations, we non-dimensionalize Eqs. (1) and (2) by substituting Eq. (2) into Eq. (1) and dividing by md to obtain

$$W''(\tau) + 2\gamma W'(\tau) + W(\tau) = a\Omega_0^2 \cdot C_L(\tau) \ldots\ldots\ldots(3)$$

where the prime indicates differentiation with respect to the argument, $W = w/d$, $\omega_n = \sqrt{K/m}$, $\tau = \omega_n t$, $\gamma = C/2m\omega_n$, $a = \rho d^2 L/8\pi^2 St^2 m$, $\Omega o = f_s/f_n = St(V/f_n d)$. Such that ω_n denotes the natural frequency of the member in radians per second, f_s denotes the frequency of vortex shedding ($f_s = StV/d$), f_n is the natural frequency of the member in cycles per second for the $n^{\underline{th}}$ mode of vibration, and St denotes the Strouhal number.

The nature of the fluid behavior is complex. It is generally agreed, however, that it is nonlinear in nature as exemplified by the "lock-in" phenomenon. We recall that the lock-in phenomenon describes a finite-spectrum resonance of a specimen, in contrast to a point-spectrum or a delta function (spikes)

type of resonance which is characteristic for a linear system.

In a linear system, the resonance will occur only if the Strouhal frequency is exactly equal to the natural frequency of the elastic system. In a nonlinear system, on the other hand, the resonance will begin even when the Strouhal frequency is somewhat less than the natural frequency and will persist even after the Strouhal frequency exceeds the natural frequency by a substantial margin. Within this range, the natural and the Strouhal frequencies lock-in to a common frequency, which is close to the natural frequency of the system.

Following Hartlen-Currie, we postulate that the fluid action obeys the best-known and perhaps the simplest nonlinear oscillator, the van der Pol model:

$$C_L''(\tau) - \varepsilon\Omega_0 C_L'(\tau) + \frac{\zeta}{\Omega_0}\left[C_L'(\tau)\right]^3 + \Omega_0^2 C_L(\tau) = b\,W'(\tau) \quad \ldots(4)$$

The van der Pol parameters ε and ζ, and the coupling coefficient b are assumed to be constants.

(2) Solution of Hartlen-Currie Equations

By assuming that the force excitation and the beam displacement response oscillate at the same circular frequency ω_c (close to ω_n), that both have near sinusoidal waveform with little amplitude modulation, and that the excitation leads the response by some phase angle Φ, we seek solutions of Eqs. (3) and (4) of the form

$$W = \bar{W} \sin \Omega\tau \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5a)$$

$$C_L = \Gamma \sin(\Omega\tau + \Phi) \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5b)$$

$$\Omega = \omega_c / \omega_n \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5c)$$

where, to the zeroth order of approximation, $\bar{W}$ and Γ are constant amplitudes.

Using Eqs. (5 a,b,c) in Eq. (3) and equating coefficients appropriately shows that C_L and Γ can be determined in terms of the as yet undertermined Ω and $\bar{W}$ through

$$\Gamma \cos \Omega\tau = (1 - \Omega^2)\bar{W} / a\Omega_0^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (6a)$$

$$\Gamma \sin \Omega\tau = 2\gamma\Omega\bar{W} / a\Omega_0^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (6b)$$

Substituting Eqs (6a,b) into Eq. (4) and equating the like coeffecients of the trigonometric functions we obtain,

$$2\gamma\Omega(\Omega_0^2 - \Omega^2) - \varepsilon\Omega_0\Omega(1 - \Omega^2) - ab\Omega_0^2\Omega + \frac{3\zeta\bar{W}^2}{4a^2\Omega_0^5}\Omega^3(1 - \Omega^2)Z = 0 \quad \ldots (7a)$$

$$(1 - \Omega^2)(\Omega_0^2 - \Omega^2) + 2\varepsilon\gamma\Omega_0\Omega^2 - \frac{3\zeta\bar{W}^2}{4a^2\Omega_0^5} 2\gamma\Omega^4 Z = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (7b)$$

where $Z = (1 - \Omega^2)^2 + 4\gamma^2\Omega^2$.

Eliminating $\bar{W}^2$ and understanding that $Z \neq 0$, we obtain

$$(\Omega_0^2 - \Omega^2)Z - 2ab\gamma\Omega_0^2\Omega^2 = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (8a)$$

or $$\Omega_0/\Omega = (1 - 2ab\gamma\Omega^2/Z)^{-\frac{1}{2}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (8b)$$

We note in passing that there are three constants to be calibrated: b, ε and ζ. The additional condition can be obtained

from the complementary solution of Eq. (4). By setting the left-hand side of Eq.(4) equal to zero, it is well-known that the solution is

$$\bar{C}_L = \sqrt{\frac{3\,\varepsilon}{4\,\zeta}} \qquad \text{.....(9)}$$

which provides the needed additional condition to evaluate the three unknown constants.

(3) Calibration to Narita Data

The original Hartlen-Currie model was calibrated for a vibrating cylinder with satisfactory results. We propose to calibrate the model for a vibrating H-beam. The only known H beam experiment applicable to the present case was conducted by Narita. We shall summarize the finding as follows:

$$\mu = \frac{\rho d^2 L}{m} = 5.59 \times 10^{-3}$$

$$\gamma = 2.67 \times 10^{-2}$$

$$\bar{C}_L = 1.15$$

$$w_{max}/d^* = 0.09 \quad @\ \Omega_0 = 1.06$$

From the above data we can compute

$$a = \frac{\mu}{8\pi^2 St^2} = \frac{7.08}{St^2} \times 10^{-5}$$

*Note: The deflection arrived at using the Hartlen Currie Model represents the mean deflection of the beam. So W_{max} should be considered as $\bar{W}_{max}$ as shown in Fig. 11.

Narita did not calculate the Strouhal number in this case which we estimated to be in the neighborhood of 0.125 to 0.134. Through a parametric study the best fit for Eqs.(7b) and (9) was given by

$$St = 0.130$$
$$b = 1.5$$
$$\varepsilon = 0.5$$

Figures 32,33,34 show how these data correspond to Narita's experimental results. Figure 33 shows that with b=7.5 there was excellent agreement between experimental observations and analytical predictions of the frequency data. For the more important amplitude response analysis, however, it was found that a value of b=1.5 and ε=0.5 provided the closest fit to Narita's observed maximum amplitude response of 0.0925 at Ω_o=1.06. Figure 34 shows the result of the parametric study for frequency response using b=1.5 while Figure 31 show the amplitude response correlation between experimental and analytical results. The analytical results note a maximum amplitude of 0.1092 at Ω_o = 1.06 which will yield slightly higher deflections (on the order of 18%) over Narita's experimental observations. This will provide an added safety factor in analyzing and designing for maximum deflection.

(4) Comments

It is seen that Hartlen-Currie Model also gives a satisfactory result for vibrating H beam. Its accuracy leaves much room for improvement. One possible candidate is Skop-Griffin Model which contains two extra parameters. This model requires much more labor in calibration. Other shortcomings of Hartlen-Currie Model are:

(1) it predicts a frequency hysteresis loop which has never been observed in the experiments
(2) it fails to yield accurate information beyond the maximum amplitude; in fact, W will eventually become an imaginary number which is absurd.

Figure 11 shows a relation between the amplitude and the damping coefficient which may be useful in studying the real beam response.

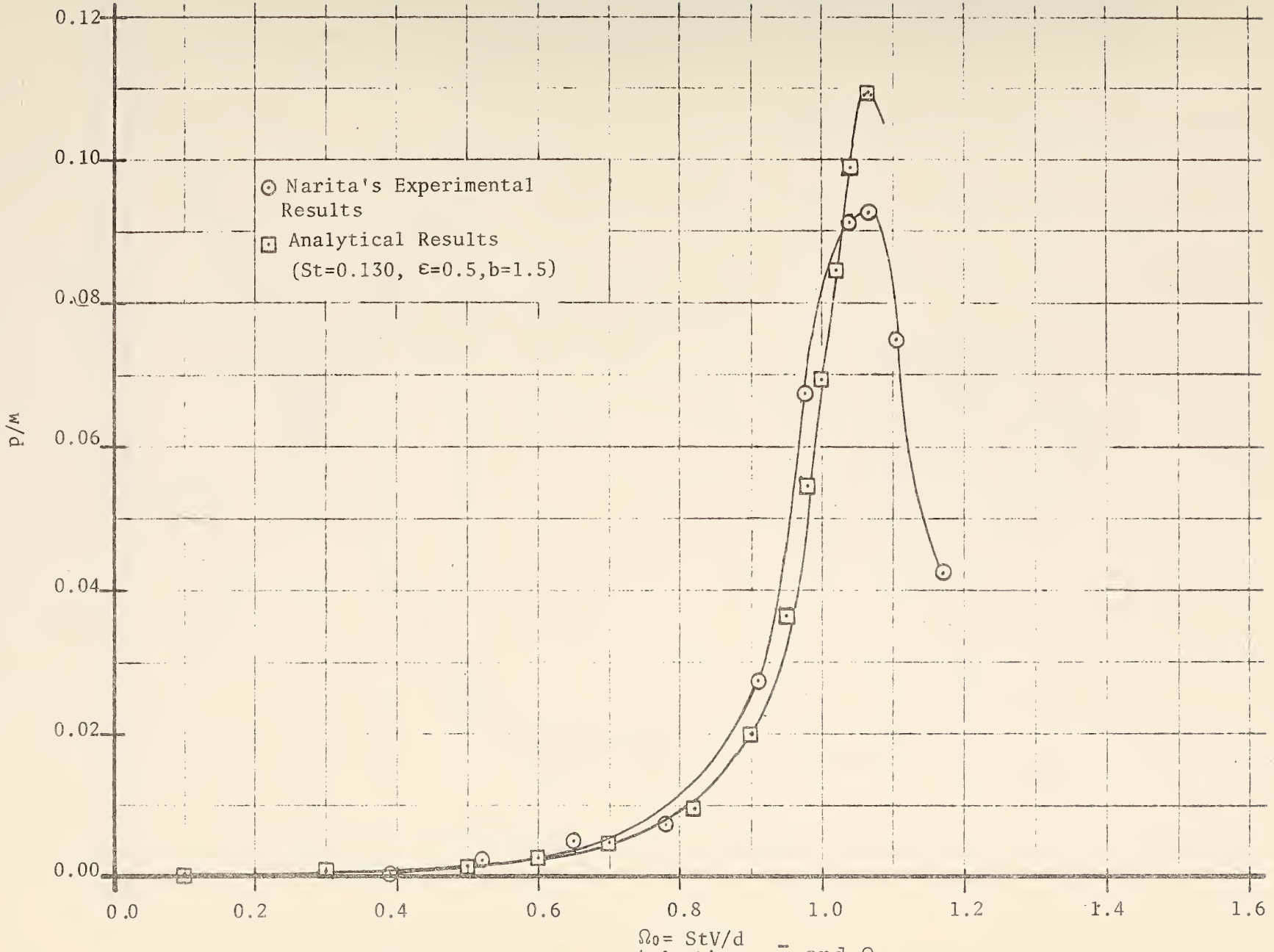


Fig. 32 Calibration of Hartlen-Currie Model with Given $\bar{w}$ and Ω_0 .

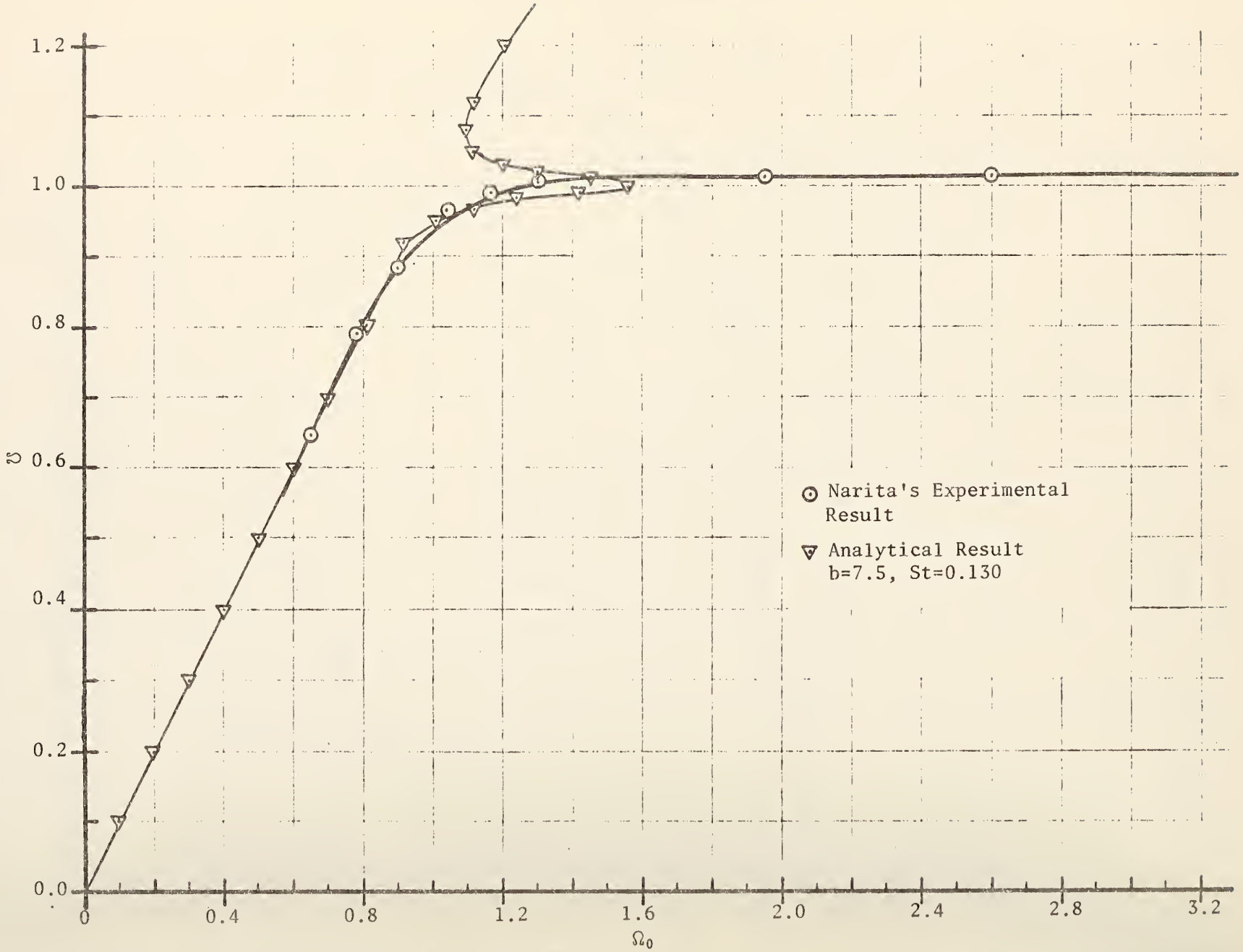


Fig. 33 Verification of Hartlen Currie Model

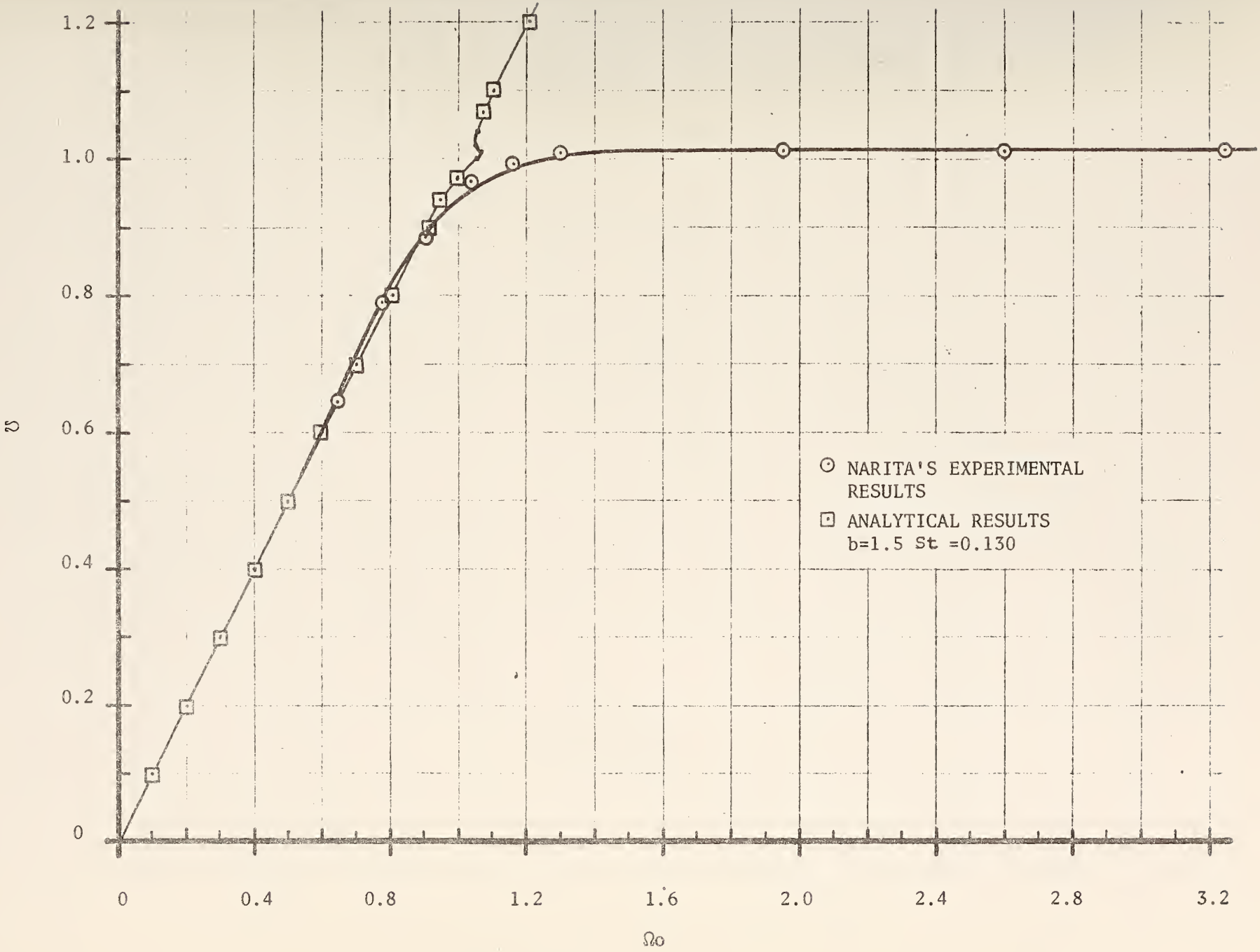


Fig. 34 PARAMETRIC STUDY FOR HARTLEN CURRIE MODEL

III. RESPONSES IN SUPERCRITICAL FLOW

The equation of motion of a continuous system takes the general form

$$m(X)\ddot{w}(X,t) + c(X)\dot{w}(X,t) + L(w(X,t)) = F(X,t) \quad (1)$$

where X is the coordinate position of a generic point in the continuous structure, m(X) is the mass density per unit length, w(X,t) is the displacement, c(X) is a viscous damping coefficient*, L(·) is a selfadjoint linear differential operator, and F(X,t) is an arbitrary forcing function. Note that X and w(X,t) are one dimensional in the present context but may be interpreted as vectors in two or three dimension cases.

Examples of the form that L may take are

$$L(\cdot) = T\frac{\partial^2}{\partial x^2}(\cdot) \qquad \text{for a vibrating string,}$$

$$\text{"} = \frac{\partial^2}{\partial X^2}\left(EI\frac{\partial^2}{\partial X^2}(\cdot)\right) \qquad \text{for a vibrating beam,}$$

and $$\text{"} = \frac{\partial^2}{\partial X^2}EI\frac{\partial^2}{\partial X^2}(\cdot) - T\frac{\partial^2}{\partial X^2} \qquad \text{for a vibrating beam with tension.}$$

To solve (1) we assume sufficient conditions to insure w(X,t) has an orthogonal expansion in normal modes $w_n(X)$ of the form $w(X,t) = \sum_{n=1}^{\infty} w_n(X)q_n(t)$, where the generalized coordinates $q_n(t)$ remain to be determined. Using this expansion we may

---

*Hysteretic or structural damping introduces only minor changes.

rewrite (1) as

$$m(X)\sum_{n=1}^{\infty} w_n(X)\ddot{q}_n(t) + c(X)\sum_{n=1}^{\infty} w_n(X)\dot{q}(t) + \sum_{n=1}^{\infty} L(w_n(X))q_n(t)$$

$$= F(X,t). \qquad (2)$$

Pick a particular normal mode $w_r(X)$, multiply (2) by it and integrate with respect to X to obtain the infinite system of ordinary differential equations in t,

$$M_r\ddot{q}_r + 2\pi M_r f_r \gamma_r \dot{q}_r + M_r 4\pi^2 f_r^2 q_r = P_r(t), \quad (r=1,2\ldots) \quad (3)$$

where $M_r = \int_o^\ell m(X)w_r^2(X)\,dX,$

$$2\pi M_r f_r \gamma_r = \int_o^\ell c(X)w_r^2(X)\,dX,$$

and $P_r(t) = \int_o^\ell F(X,t)w_r(X)\,dX.$

We point out that to obtain (3), we assumed the orthogonality conditions

$$\int_o^\ell m(X)w_r(X)w_n(X)\,dX = \delta_{rn}M_r$$

and $\int_o^\ell c(X)w_r(X)w_n(X)\,dX = \delta_{rn}4\gamma_r\pi M_r f_r$ (i.e., we assume no frictional coupling between the modes) where γ_r is the generalized damping term, commonly known as the "viscous damping" (i.e., π radians out-of-phase with the velocity $\dot{w}$ but, unlike the hydrodynamic damping, is independent of the magnitude of the velocity and the f_r's are the natural frequencies derived from the relationship $L(x_n) = m(2\pi f_n)^2 w_n$.

Equations (3) govern each individual natural mode of

vibration and consequently, we have in effect uncoupled all the modes of vibration. By design, equations (3) have the same form as equations of motion of a simple oscillator. Thus methods which have been previously developed for the treatment of random vibrations of discrete mechanical systems can be used here in developing analogous techniques for the treatment of random vibrations of continuous systems.

Returning to the solving of system (3), take the Fourier transform and obtain

$$\bar{q}_r(f) = H(f)\bar{P}_r(f)$$

where $$\bar{q}_r(f) = \int_{-\infty}^{\infty} q_r(t) e^{-i2\pi ft}\, dt,$$

$$\bar{P}_r(f) = \int_{-\infty}^{\infty} P_r(t) e^{-i2\pi ft}\, dt,$$

and $$H(f) = \frac{1}{4\pi^2 M_r\{(f_r^2 - f^2) + i\gamma_r f_r f\}}.$$

Let $h(t) = \int_0^{\infty} H(f) e^{i2\pi ft}\, df$. Then we obtain the solution

$$q_r(t) = \int_{-\infty}^{t} h(t - \tau) P_r(\tau)\, d\tau$$

$$= \int_0^{\infty} h(\tau_1) P_r(t - \tau_1)\, d\tau_1. \qquad (4)$$

The next step in the treatment of this continuous system is the development of relationships among the statistical properties of the physical and modal excitations. These are of primary concern because the original influences on the

structure were not specified in any manner and so are assumed to be random processes. To simplify the considerations, we assume these random processes to be stationary, i.e. invariant under time shifts. It follows then that the autocorrelation function $F_w(X_A,\tau)$ associated with the solution of (1) will be a function of only the time lag τ for any given point X_A. Specifically, we have (where $E(\cdot)$ represents expected values) that

$$R_w(X_A,\tau) = E\{w(X_A,t)\ \ w(X_A,t+\tau)\}$$

$$= \sum_r \sum_s w_r(X_A) w_s(X_A)\ \ R_{q,rs}(\tau) \qquad (5)$$

where $R_{q,rs}(\tau) = E\{q_r(t)q_s(t+\tau)\}$.

We must calculate $R_{q,rs}(\tau)$. To wit, since

$$q_r(t)q_s(t+\tau) = \int_o^\infty \int_o^\infty h(\tau_1)h(\tau_1)P_r(t-\tau_1)P_s(t-\tau_2+\tau)\, d\tau_1 d\tau_2$$

where $$P_r(t-\tau_1)P_s(t-\tau_2+\tau) = \int_o^\ell \int_o^\ell F(S_x,t-\tau_1)w_r(X_1)\, F(X_2,t-\tau_1+\tau)w_s(X_2)\ dX_1\, dX_2.$$

then $$R_{q,rs}(\tau) = \int_o^\infty \int_o^\infty h(\tau_1)h(\tau_2)\{\int_o^\ell \int_o^\ell R_F(X_1,X_2;\tau)w_r(X_1)w_s(X_2)\,dX_1\,dX_2\}d\tau_1 d\tau_2$$

where $R_F(X_1,X_2;\tau)$ is the autocorrelation function associated with the forcing term $F(X,t)$.

Next we wish to determine the spectral density function $S_w(X_1;f)$ which corresponds to the autocorrelation function $R_w(X_1,\tau)$.

This is done by taking the Fourier transform of (5) and using the Wiener-Khinchin relation $S(f) = \int_{-\infty}^{\infty} 2e^{i2\pi f\tau} R(\tau)d\tau$ between a spectral density $S(f)$ and its associated autocorrelation function $R(\tau)$.

We get

$$S_w(X_1;f) = \sum_r \sum_s w_r(X_1)w_s(X_1)S_{q,rs}(f) \qquad (6)$$

where $$S_{q,rs}(f) = H_r(-if)\, H_s(if)\, \{\int_o^\infty \int_o^\infty S_F(X_1,X_2;\tau)w_r(X_1)w_s(X_2)\, dX_1dX_2.\}$$

$S_F(X_1,X_2;\tau)$ is naturally, the spectral density associated with $R_F(X_1,X_2;\tau)$.

In our case, the frequencies are distinct and the damping is small so that the peaks are well separated. We can approximate by neglecting the cross products and obtain the simpler expression

$$S_w(X_A,f) = \sum_r w_r^2(X_A)S_{q,r}(f)$$

where $S_{q,r}(f) = |H_r(f)|^2 \cdot \{\int_o^\ell \int_o^\ell w_r(X_1)w_r(X_2)S_F(X_1,X_2;f)\, dX_1dX_2\}$.

If we assume that the lift force is spatially independent i.e. if there is perfect coherence spanwise, then $S_F(X_1,X_2;f) = S_F(f)$ and hence

$$S_{q,r}(f) = |H_r(f)|^2 \{\int_o^\ell \int_o^\ell w_r(X_1)w_r(X_2)S_F(f)dX_1dX_2\}.$$

It therefore follows (by taking a mean value) that

$$E\{q_r^2(t)\} = \int_o^\infty S_F(f) \left(\int_o^\ell w_r(X)dX\right)^2 \cdot |H_r(f)|^2\, df$$

$$= S_F(f)\Big|_{f=f_o} \left(\int_o^\ell w_r(X)dX\right)^2 \int_o^\infty |H_r(f)|^2 df.$$

We must now evaluate $\int_0^\infty |H_r(f)|^2 df$. Using the method of residues, one finally gets

$$\int_0^\infty |H_r(f)|^2 \, df = \frac{1}{64\pi^3 M_r^2 \gamma_r f_r^3}.$$

(In the engineering analysis the hysteretic damping or structural damping is denoted by η_r which should satisfy

$$M_r \ddot{q}_r + M_r (2\pi f_r)^2 \{1 + i\eta_r\} q_r = P_r(t). \tag{3a}$$

In this case

$$H(f) = \frac{1}{4\pi^2 M_r \{(f_r^2 - f^2) + i\eta_r f_r^2}$$

so that $$|H(f)|^2 = \frac{1}{(4\pi^2 M_r)^2 \{(f_r^2 - f^2)^2 + \eta_r^2 f_r^4\}}$$

and thus $$\int_0^\infty |H(f)|^2 \, df = \pi \frac{1}{(4\pi^2 M_r)^2 f_r^3 \cdot 4\sqrt{\tfrac{1}{2}(\sqrt{1 + \eta_r^2} - 1)}(\sqrt{1 + \eta_r^2})}$$

which for $\eta_r << 1$ reduces approximately to

$$\int_0^\infty |H(f)|^2 df = \frac{1}{4M_r^2 (2\pi f_r)^3 \eta_r}$$

which correlates nicely with the preceding.) Now we invoke the fact that for sharp-peaked $|H(f)|^2$, f_0 is equal to f_r approximately and that the rms $q_r(t)$ is the square root of $E\{q_r^2(t)\}$. Thus we have as an expression for the root mean square of $q_r(t)$:

$$\text{rms } q_r(t) = \frac{\int_0^\ell w_r(X) \, dX}{8 M_r} \sqrt{\frac{S_F(f_r)}{\pi^3 f_r^3 \gamma_r}}.$$

Since $S_F(f_r)$ is usually normalized, i.e.

$\int_0^\infty S_f(f_r)\, df = \int_0^\infty S_f(St)\, d(St) = 1$ where St is the Strouhal number and

$S_F(f_r) = (\frac{1}{2}\rho_a C_L dV^2)^2\, S_f(f_r)^*$, we obtain

$$rms(q_r) = \frac{\int_0^L w_r\, dx}{8 M_r} (\tfrac{1}{2}\rho_a C_L dV^2) \sqrt{\frac{S_f(f_r)}{(\pi f_r)^3 \gamma_r}}$$

Finally, returning to the solution S(X,t),

$$rms(w)\Big|_{X=X_A} = \sum_r w_r(X_A) \cdot rms(q_r)$$

$$= \sum_r \frac{w_r(X_A) \int_0^L w_r\, dx}{8 M_r (\pi)^{3/2} f_r^2} (\tfrac{1}{2}\rho_a C_L dV^2) \sqrt{\frac{S_f(f_r) f_r}{\gamma_r}}$$

$$= \sum_r \frac{w_r(X_A) \int_0^L w_r\, dx}{16 M_r (\pi)^{3/2} f_r^2} (\rho_a C_L dV^2) \sqrt{\frac{S_f(St)\, St}{\gamma_r}} . \quad (7)$$

$$rms\ M\Big|_{X=X_A} = rms\ EI \frac{\partial^2 w}{\partial x^2}\Big|_{X=X_A} \quad (8)$$

To evaluate Equation (8), the mode shapes must be twice differentiated, which is complicated to evaluate numerically, except for simply-supported beams. In general, it is simpler to use the deflection-moment relationship as derived in a later section. (See Part C , Chapter III.)

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*The quantity $(\frac{1}{2}\rho_a C_L dV^2)$ is the lifting force.

PART C

DESIGN PROCEDURES AND NUMERICAL EXAMPLES

I. NATURAL FREQUENCIES, MODES AND WIND VELOCITIES

(1) General Case for Bending and Torsion for Thin Open Sections

The general equations developed above were used to develop the following design procedure. The designer, having made a preliminary choice of a beam for use in the structure, can easily determine the wind velocities which will cause the beam to vibrate in resonance. First, the value of $\sqrt{P}$ for bending can be calculated as:

$$\sqrt{P} = \sqrt{\frac{TL^2}{EI}} \qquad \text{for open or closed cross sections}$$

where T = Tensile force on beam

L = Length of beam

E = Modulus of elasticity

I = Moment of inertia about axis of vibration

and for torsion:

$$\sqrt{P} = \sqrt{\frac{[GC + (T/A) I_p] L^2}{EC_w}} \qquad \text{for open cross sections.}$$

Knowing the value of P the designer can go to the provided graphs of $\sqrt{P}$ vs. $\sqrt[4]{Q}$ (Figs. 1-10) and determine the values of $\sqrt[4]{Q}$ for the first three modes of vibration on the given beam of open cross section. These graphs* consider the end support conditions of the beam and provide results for beams with both ends having simple supports, both ends having fixed supports, and a wide variety of end support combinations between these two extreme conditions. For beams of closed cross section, the designer can use the average values of $\sqrt[4]{Q}$ given in Table 1.

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* For more complete graphs including unsymmetric cases, see Appendix B, Figs. 36 - 84.

The value of $\sqrt[4]{Q}$ is related to the natural frequency of the beam as follows:

$$\sqrt[4]{Q} = \sqrt[4]{\frac{\rho_m A \omega_n^2 L^4}{EI}}$$ for bending of all cross sections (open or closed)

where:

ρ_m = Mass density

A = Cross sectional area

ω_n = Natural frequency

L = Length of beam

E = Modulus of elasticity

I = Moment of inertia of section about axis of vibration

n = Mode of vibration (n = 1,2,3)

$$\sqrt[4]{Q} = \sqrt[4]{\frac{\rho I_p \omega_n^2 L^4}{EC_w}}$$ For torsion of open cross section

or $$\sqrt[4]{Q} = \sqrt[4]{\frac{\rho_m I_p \omega_n^2 L^2}{GC}}$$ for torsion of closed cross section.

(For derivation see next section.)

Where:

I_p = Polar moment of inertia

C_w = Warping constant

G = Modulus of rigidity

C = Torsional constant

For the beam with both ends simply supported the relationship between $\sqrt{P}$ and $\sqrt[4]{Q}$ is simple and is given as:

$$Q = n^4 \pi^4 + n^2 \pi^2 P \qquad n = 1,2,3$$

However the relationship between P & Q becomes complicated for other end support conditions. Therefore, the graphs (Fig. 1 - 10) have been worked out by computer analysis to provide the designer with a simple means of finding the value of $\sqrt[4]{Q}$.

After determining the values of $\sqrt[4]{Q}$ for the first three modes of vibration from the graphs the designer can use them to directly determine the natural frequencies that correspond to them. The designer can find the Strouhal number corresponding to the shape of his beam from the material provided in Chapter IV, part A. The wind velocity related to the natural frequency and Strouhal number is:

$$V = \frac{\omega_n d}{2 \pi St}$$

Where:

V = Wind velocity

St = Strouhal number

ω_n = Natural frequency

d = Depth of section transverse to wind direction

Alternately, the designer can compute the wind velocity directly, knowing the Strouhal number and the values of $\sqrt[4]{Q}$. He must determine a value of Z which relates $\sqrt[4]{Q}$ and St as follows:

For bending of open or closed cross sections, we know that:

$$Q = \frac{\rho A \omega_n^2 L^4}{EI} \quad , \text{ and } \quad St = \frac{\omega_n d}{2\pi V}$$

therefore, $$\sqrt{Q} = \sqrt{\frac{\rho A}{EI}} \; \frac{L^2 2\pi V}{d} \; St$$

or, we define $$Z = \frac{\sqrt[4]{Q}}{\sqrt{St}}$$

$$Z = \sqrt[4]{\frac{\rho_m A L^4 V^2 4\pi^2}{EId^2}}$$

A similar approach can be taken to show that for torsion:

$$Z = \sqrt[4]{\frac{\rho_{mp} 4\pi^2 V^2 L^4}{EC_w d^2}}$$ For open cross sections

or

$$Z = \sqrt[4]{\frac{\rho_{mp} 4\pi^2 V^2 L^2}{GCd^2}}$$ For thin closed cross sections,

Computing the values $Z = \sqrt[4]{Q}/\sqrt{St}$, or from Fig. 35, and using the definition of Z, the designer can easily find the wind velocities corresponding to each mode of vibration from the following relations:

$$V = Z^2 \frac{d}{2\pi L^2} \sqrt{\frac{EI}{\rho A}_m}$$ For bending of open or closed cross sections

and

$$V = Z^2 \frac{d}{2\pi L^2} \sqrt{\frac{EC_w}{\rho I}_{m\,p}}$$ For torsion of open cross sections

or

$$V = Z^2 \frac{d}{2\pi L} \sqrt{\frac{GC}{\rho I}_{mp}}$$ For torsion of closed cross sections.

Knowing the wind velocity which will cause vibration in the beam being considered and the weather data of wind velocities in the design area, the designer can decide whether the selected beam is sufficient or whether another section should be used.

Examples of this design procedure can be found in Examples 1 to 4.

(2) Natural Frequencies for Torsional Vibration of Thin Closed Section

The governing equation for bending of a structural member with a thin, closed cross section such as a box or circular pipe section, is the same as that for a member with an open section and the value of $\sqrt[4]{Q}$ can be obtained as usual from the graphs provided (Figs.1-10). However, for a member with a thin, closed cross section in torsion, C_w equals zero. The general governing equation:

$$\frac{\rho_m I_p \omega^2 L^4}{EC_w} = n^4\pi^4 + n^2\pi^2 \frac{[GC + (T/A) I_p] L^2}{EC_w}$$

reduces to:

$$\frac{\rho_m I_p \omega^2 L^2}{GC} = n^2\pi^2 + n^2\pi^2 \frac{(T/A) I_p}{GC}$$

which is of the form $Q = n^2\pi^2 + n^2\pi^2 P$. Therefore, for thin, closed sections, these parameters are non-dimensionalized,

$$P = \frac{(T/A) I_p}{GC}$$

$$Q = \frac{\rho_m I_p \omega_n^2 L^2}{GC}$$

With this form of P, the values of $\sqrt{P}$ can easily be calculated for any member being analyzed just as in the case of an open cross section.

Within the range of allowable tensile stress (from T/A = 0 ksi to T/A = 60 ksi)*, the values of $\sqrt[4]{Q}$ for thin, closed cross sections

* American Institute of Steel Construction - Manual of Steel Construction.

vary over a small range. Over this small range the average values of $\sqrt[4]{Q}$ are:

Mode 1, $\sqrt[4]{Q} = 1.77$

Mode 2, $\sqrt[4]{Q} = 2.51$

Mode 3, $\sqrt[4]{Q} = 3.07$

which correspond to a tensile stress of T/A = 20 ksi.

These values can be used for all shapes of thin,closed cross sections in torsion having any specified axial tension with an expected error of well below 1.0%.

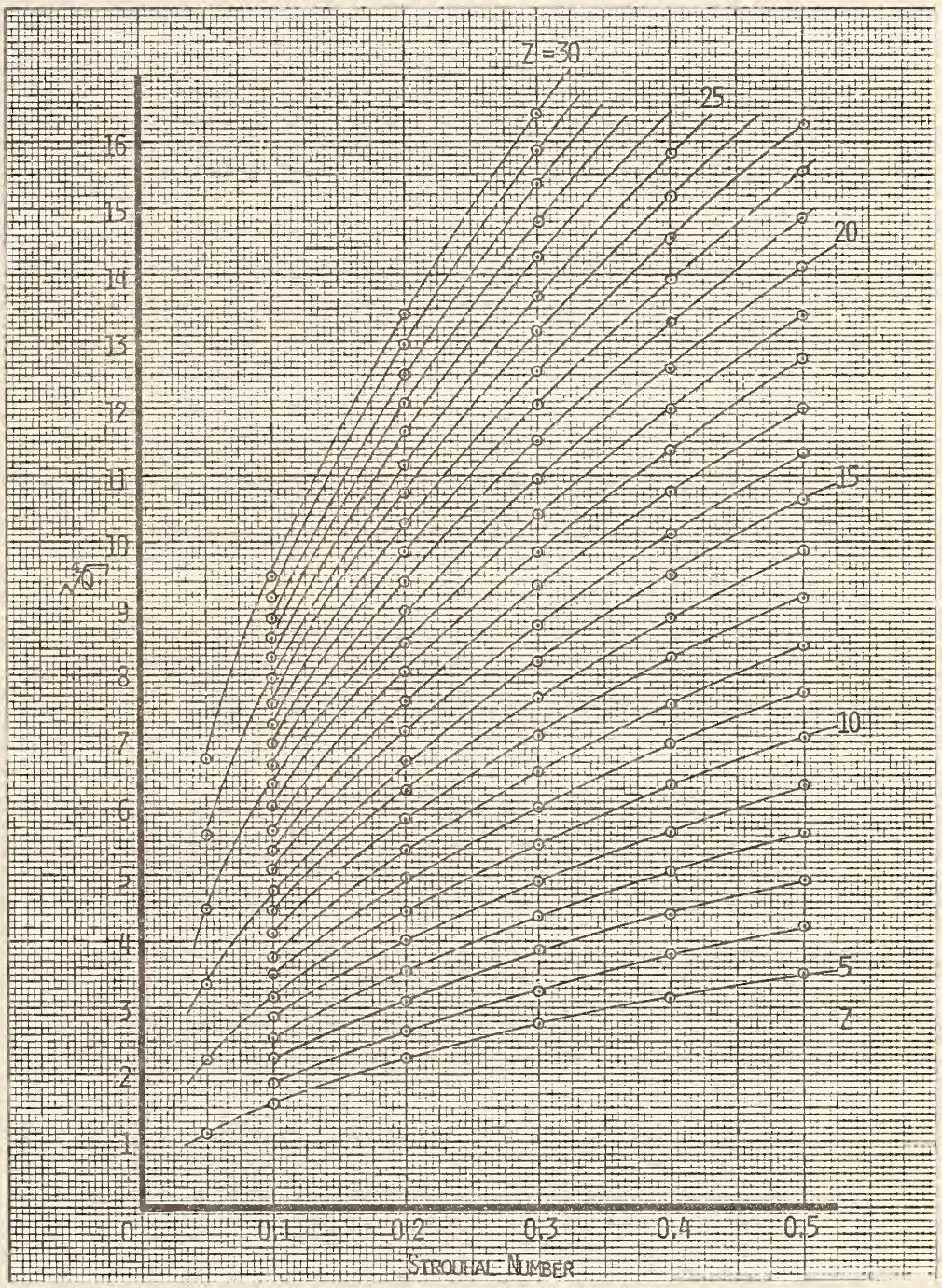


FIG. 35 VELOCITY COEFFICIENTS Z RELATED TO Q & ST

(3) DESIGN EXAMPLES

This section will provide practical examples that demonstrate the application of the previously presented theory. The examples assume that the designer has already chosen a particular structural shape for use and wishes to calculate the wind velocities which correspond to the member's first three modes of vibration.

Depending on how the structural members are connected, the designer has to determine the end support conditions of the member. After deciding this, simple calculation and the charts provided within this report will quickly lead to the determination of the wind velocities that will directly affect the member.

Historical data of wind velocities in the vicinity of the structure can be obtained and consulted, giving the designer an accurate understanding of whether the given member will be affected by existing site winds. If the wind velocities commonly experienced in the site area correspond with those calculated the designer may decide either to choose a different member for the structure or to modify the structure using the methods discussed within this report to insure minimum wind induced vibration.

Previous studies have shown that circular cylinders behave in an unusual manner once the Reynolds number of the airstream flow reaches a value above 1.0×10^5. At this point the member enters a transitional range which extends to a Reynolds number of about 4×10^5 depending on

the upstream turbulence and local disturbances. Within this range, the circular cylinder will jump from a subcritical state where vibrations concentrate at the fundamental natural frequency of the member to a supercritical state where random vibration occurs. In the supercritical state vibrations have wide dispersion and a wind velocity corresponding to the fundamental mode of vibration excites the third mode of vibration of the member.

Whether such an occurance is possible for structural cross sections other than circular was not evident in the literature researched for this report. If the future research should show this phenomenon to be a general rule then the procedure outlined in example 5 can be applied for checking the member in the supercritical range. Otherwise, the subcritcal flow will be the dominant criterion of analysis regardless of the Reynolds numbers. After calculating the wind velocities that will directly affect the chosen member, the designer can determine whether the member will undergo subcritical or supercritical vibration. If the flow is in the transitional or supercritical range the member should be analyzed considering random vibrational effects with modification made accordingly.

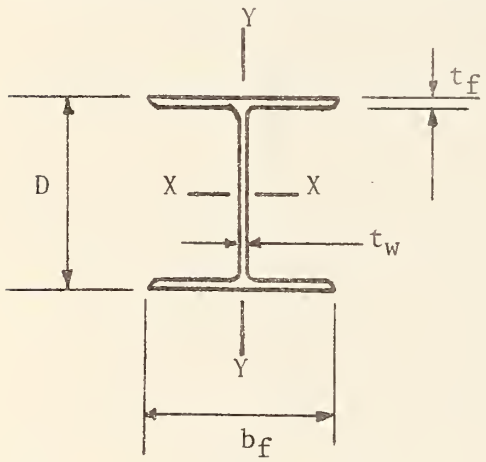
It is therefore, the aim of these examples to provide insight on how problems can be realistically evaluated. Various end conditions, open and closed cross sections, and vibration levels will be examined.

Hopefully these examples will provide significant demonstration of the theory developed earlier and its application in the design process to reduce or avoid possible dangerous affects of wind induced vibrations.

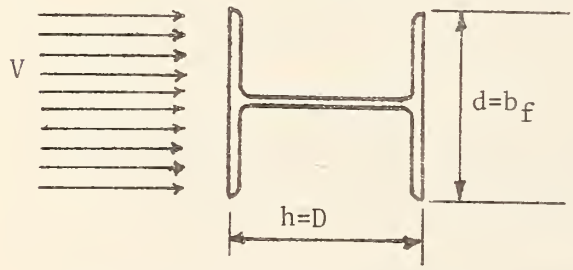
DESIGN EXAMPLE NO. 1

Assume a beam HP 12 x 74 is to be examined. It is 45 feet long, carries a tensile load of 87.2 KIPS, and has simple supports at each end. ($\sigma_1 = \sigma_2 = 0$)

With this preliminary information, the designer can begin the analysis. First the properties of the HP 12 x 74 section should be determined. The Manual of Steel Construction put out by the American Institute of Steel Construction provides easy access to such information.



Orientation in the wind



Properties for Designing (AISC Manual p.1-48)

HP 12 x 74 section

Area = 21.8 in.^{2}

Depth (D) = 12.12 in.

Width (b_f) = 12.217 in.

Thickness:
Flange (t_f) = 0.607 in.
Web (t_w) = 0.607 in.

Elastic Properties:

xx - axis	yy - axis
I = 566 in.^{4}	I = 185 in.^{4}
S = 93.4 in.^{3}	S = 30.2 in.^{3}
r = 5.10 in.	r = 2.91 in.
	I_p = 751 in.^{4}

Modulus of elasticity (E) = 29 x 10^3 ksi
Warping constant (C_w) = 6120 in.^{6}
Torsional constant (C) = 2.97 in.^{4}
Poisson's ratio (Γ) = 0.3 (for steel)
Modulus of rigidity (G) = $\frac{E}{2(1+\Gamma)}$ = 1.115 x 10^4 ksi

Once the specific properties for the section are available, the designer can begin the calculations by solving for the bending and torsional values of $\sqrt{P}$.

For Bending:

$$P_B = \frac{TL^2}{EIyy^*} = \frac{(87.2 \text{ kips})(45\text{ft.})^2(144 \text{ in.}^2/\text{ft}^2)}{(29 \times 10^3 \text{ksi})(185 \text{ in.}^4)} = 4.74$$

$$\sqrt{P}_B = 2.177$$

for torsion

$$P_T = \frac{(GC + I_P T/A)L^2}{EC_W}$$

$$= \frac{(1.115 \times 10^4 \text{ksi})(2.97 \text{ in.}^4) + (751 \text{ in.}^4)\left(\frac{87.2 \text{ kips}}{21.8 \text{ in.}^2}\right)(45\text{ft})^2(144 \text{ in.}^2/\text{ft}^2)}{(29 \times 10^3 \text{ksi})(6120 \text{ in.}^6)}$$

$$P_T = 5.936 \times 10^1$$

$$\sqrt{P}_T = 7.705$$

With the above values of $\sqrt{P}$ for bending and torsion and with knowledge of the end support conditions, the designer can easily read the values of $\sqrt[4]{Q}$ for the first three modes of vibration from Figure 1, page 15.**

---

*Vibrations will occur about yy - axis for orientation of member in this example.

**Note: For cases where the member is simply supported at both ends, the relationship between $\sqrt{P}$ & $\sqrt[4]{Q}$ reduces to:

$$\sqrt[4]{Q} = n^4\pi^4 + n^2\pi^2\sqrt{P}$$

If desired, the designer can directly calculate $\sqrt[4]{Q}$ but the charts provided are accurate and easily used.

MODE n	BENDING $\sqrt[4]{Q}$	TORSION $\sqrt[4]{Q}$
1	3.49	5.00
2	6.49	7.90
3	9.55	10.70

The next step is to calculate a value Z for both bending and torsion. This value will be used to calculate the velocity of wind corresponding to the first three modes of vibration. The designer must choose an appropriate Strouhal number for the section being analyzed. For this example the Strouhal number for a "H" shaped cross section is:

$$S_t = 0.12^{*}$$

then Z can be calculated** from the following relationship:

$$Z = \sqrt[4]{Q} \div \sqrt{S_t}$$

and the values of Z for this example are as follows:

MODE n	BENDING Z_B	TORSION Z_T
1	10.075	14.434
2	18.735	22.805
3	27.569	30.888

Now the wind velocities can be computed using the relationships:

For bending:

$$V_n = Z_B^2 \frac{d}{2\pi L^2} \sqrt{\frac{EI}{\rho_m A}}$$

---

*Reference material within this report provides Strouhal number information for various cross sections.

**Values of Z can also be read directly from chart provided (Fig. 35, p. 113) if desired.

where: I = The moment of inertia along the axis about which the vibration takes place. (For this example and section orientation, use I_{yy})

ρ_m = Mass density of the material of the member. For this example the material is steel with a density of 489 $^{lb}/_{ft^3}$, the mass density is therefore

$$\rho_m = \frac{489^{lb}/_{ft^3}}{32^{ft}/_{sec^2}} = 15.186 \frac{lb\text{-}sec^2}{ft^4}$$

$$\rho_m = 7.324 \times 10^{-4} \frac{lb\text{-}sec^2}{in.^4}$$

For torsion: $$V_n = Z_T^2 \frac{d}{2\pi L^2} \sqrt{\frac{EC_w}{\rho_m I_p}}$$

where: I_p = The polar moment of inertia of the section ($I_p = I_{xx} + I_{yy}$)

ρ_m = Mass density of the section

The values of V for this example have been carefully calculated and are summarized in the following table. Along with the Reynolds numbers that correspond to each velocity. The value of the Reynolds numbers are arrived at through the simple calculation of:

$$Re_n = \frac{V_n d}{\nu}$$

where υ = Kinematic viscosity of air ($\upsilon = 2.3 \times 10^{-2}$ $in.^2/_{sec}$)

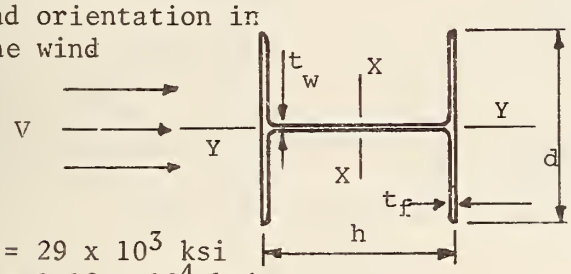
MODE	BENDING		TORSION	
n	Wind Velocity V mph(km/hr)	Reynolds Number Re	Wind Velocity V mph(km/hr)	Reynolds Number Re
1	22.292(35.876)	2.084×10^5	44.837(72.16)	4.19×10^5
2	77.088(124.06)	7.207×10^5	111.93(180.14)	10.464×10^5
3	166.92(286.63)	15.605×10^5	205.336(330.46)	19.196×10^5

With the above information relating wind velocity to the natural frequency of the member, the designer is armed with sufficient information to make a decision as to the choice of this member for the structural examining of the resulting wind velocities. The designer can readily see that the wind velocities of 22.292 mph for bending and 44.837 mph for torsional vibrations are most likely the ones to be concerned about. The larger velocities corresponding to vibrational modes 2 and 3, in most areas, will not occur too frequently. If 22 mph and 45 mph winds are a very common occurrence in the location of the structure, the designer may decide to either modify the member using methods presented in this report or choose a new member for analysis in order to reduce possible detrimental fatigue damage due to wind induced vibrations.

DESIGN EXAMPLE NO. 2

This example shall examine another "H 'shape section, this time a large built up member with both ends having fixed supports. ($\sigma_1=\sigma_2 \rightarrow \infty$ for bending and torsion)

Properties of member:
And orientation in the wind



$E = 29 \times 10^3$ ksi
$G = 1.12 \times 10^4$ ksi

Area = 38.5 in.^{2}
h = 30.0 in. (Depth of section)
d = 24.0 in. (Width of flange)
t_f= 0.5 in.
t_w= 0.5 in.
I_{xx}= 6238.208 in.^{4}
I_{yy}= 1152.302 in.^{4}
I_p = 7390.510 in.^{4}
C = 3.229 in.^{4}
Cw= 2.51×10^5 in.^{6}

The member's length is 90 feet and it carries a prevailing stress of 30ksi

The tensile load is therefore:

$$T = \sigma \times A = (30\text{ksi})(38.5\ \text{in}^2) = 1155.0 \text{ kips.}$$

Now calculate $\sqrt{P}$:

For bending: $P_B = \dfrac{TL^2}{EI_{yy}} = 40.31$, so $\sqrt{P}_B = 6.35$

For torsion: $P_T = \dfrac{(GC + I_p T/A)L^2}{EC_w} = 41.32$, so $\sqrt{P}_T = 6.43$

The values of $\sqrt[4]{Q}$ can now be read from the chart (Fig. 10) on page 24. Again using a Strouhal number of St=0.12, (for "H" shaped section), Z can be computed using $Z = \sqrt[4]{Q} \div \sqrt{St}$. The results of these efforts are summarized in the following table:

Mode	Bending		Torsion	
n	$\sqrt[4]{Q}$	Z_B	$\sqrt[4]{Q}$	Z_T
1	5.58	16.108	5.60	16.166
2	8.60	24.826	8.65	24.970
3	11.65	33.631	11.70	33.775

The velocities for the first three modes of vibration can be calculated using the following relations:

For bending $$V_n = Z_{B_n}^2 \frac{d}{2\pi L^2} \sqrt{\frac{EI_{yy}}{\rho_m A}}$$

For torsion $$V_n = Z_{T_n}^2 \frac{d}{2\pi L^2} \sqrt{\frac{EC_w}{\rho_m I_p}}$$

The velocities calculated are summarized in the following table which also show the corresponding Reynolds number calculated from:

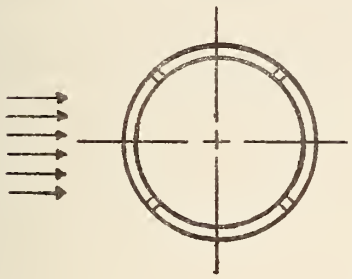
$$Re_n = \frac{V_n d}{\nu}$$

Mode	Bending		Torsion	
n	Wind Velocity V MPH(Km/hr)	Reynolds Number Re	Wind Velocity V MPH(Km/hr)	Reynolds Number Re
1	52.52(84.52)	9.645×10^5	56.39(90.75)	1.04×10^6
2	124.84(200.91)	2.292×10^6	134.53(216.51)	2.47×10^6
3	229.102(368.704)	4.208×10^6	246.14(396.13)	4.52×10^6

As previously explained, the designer at thin point must decide on the worthiness of the member in light of the above information and act accordingly.

DESIGN EXAMPLE NO. 3

This example will examine how the theory is applied to a steel pipe - 12" Ø standard weight.



Properties of Member

O.D. = 12.750 in.
I.D. = 12.000 in.
Nominal Diameter = 12 in.
Wall thk. = 0.375 in.
Area = 14.6 $in.^2$
I = 279 $in.^4$
I_p = 558 $in.^4$
Length = 40 ft.

$C = \frac{1}{2}\pi r^4 = 2035.75\ in.^4$
$C_w = 0$
$E = 29 \times 10^3$ ksi.
$G = 1.12 \times 10^4$ ksi.

Support Conditions: Both ends simply supported ($\sigma_1 = \sigma_2 = 0$)
Loading Conditions: Assume prevailing tensile stress of 35 ksi, therefore the tensile load is:

$$T = (35\ ksi)(14.6\ in.^2) = 511\ kips.$$

Calculations

1. Caclulate P for bending (Note: P for torsion = 0 because $C_w = 0$)

$$P = \frac{TL^2}{EI} = \frac{(511\ kips)(40ft)^2(144\ in.^2/ft^2)}{(29 \times 10^3 ksi)(279\ in.^4)} = 14.55$$

$$\sqrt{P} = 3.81$$

Using the above value of $\sqrt{P}$ and Fig. 1 (p. 15), the value of $\sqrt[4]{Q}$ for the first three modes of vibration in bending can be obtained while Table 1 (p.25) provides the values of $\sqrt[4]{Q}$ for torsion. Using the values of $\sqrt[4]{Q}$ and a Strouhal number for circular cylinders of 0.20, the value of Z can easily be calculated from the following relationship:

$$Z = \sqrt[4]{Q} \div \sqrt{St}$$

The following table lists the values of $\sqrt[4]{Q}$ and Z for the first three

modes of vibration in this example.

MODE n	BENDING $\sqrt[4]{Q}$	BENDING Z	TORSION $\sqrt[4]{Q}$	TORSION Z
1	3.90	8.72	1.77	3.96
2	6.75	15.09	2.51	5.61
3	9.75	21.80	3.07	6.86

The wind velocities corresponding to the first three modes of vibration can be calculated using the following relationships:

For bending: $$V_n = Z_n^2 \frac{d}{2\pi L^2} \sqrt{\frac{EI}{\rho_m A}}$$

For torsion: $$V_n = Z_n^2 \frac{d}{2\pi L^2} \sqrt{\frac{GC}{\rho_m I_p}}$$

The Reynolds numbers corresponding to the first three modes of vibration can also be computed once the velocities have been determined, as follows:

$$Re_n = \frac{V_n d}{\nu}$$

where ν = kinematic viscosity of air ($\nu = 2.3 \times 10^{-2}$ in.^{2}/sec.)

The following table shows the velocities and Reynolds numbers for this example.

Mode	Bending		Torsion	
n	Wind Velocity MPH (km/hr)	Reynolds Number Re	Wind Velocity MPH (KM/hr)	Reynolds Number Re
1	33.10(53.27)	3.23×10^5	1.85(2.98)	1.81×10^4
2	99.12(159.52)	9.67×10^5	3.72(5.99)	3.63×10^4
3	206.88(332.94)	20.17×10^5	5.56(8.95)	5.42×10^4

Note: For this case torsion seems to be the dominating design factor.

In examining the Renolds number for the first mode of vibration in bending, it can be seen that the flow falls within the transition range for circular cylinders as shown in Fig. 17, P. 47. Therefore, before making any final decisions concerning the member the designer should check for random shedding. This example will be continued in design example No. 5.

II. APPLICATION OF HARTLEN-CURRIE MODEL TO ELASTIC BEAM IN SUBCRITICAL FLOW CONDITION

From previously presented material, the natural frequency of a given beam subjected to wind forces can easily be found. The next important step the designer must face is the determination of the maximum deflection the beam will undergo for a certain mode shape due to a wind load and the corresponding stress produced in the beam due to this deflection.

If the deflection of the beam due to the wind excitation is negligible, the response can of course be determined by the conventional linear resonance theory for damped vibrations. However, the problem inherent in this approach is, if the deflection is negligible, the associated flexural stresses should also be negligible. A reasonable approach must involve the structure-fluid interaction. The only well-developed interaction model is due to Hartlen and Currie, Chapter II, Part B. Unfortunately, their model deals with a rigid beam while our present interest is focused on an elastic member which is capable of resisting bending moment. In order to use their theory for elastic beams, a suitable hypothesis must be made. As shown in Fig. 31, it is conceivable that some segment of the actual beam being analyzed will behave like the rigid model with the spring end conditions being provided by the remaining portions of the beam.

Using the Hartlen-Currie Model, for a given spring constant, the deflection of the beam can be found. Using the assumption that some segment of the beam under analysis responds as the model, the

designer has merely to determine a suitable spring constant for the segment. This can be accomplished by the following postulation: the natural frequency of the rigid beam is equal to one of the natural frequencies of the elastic beam, i.e., the natural frequency of the elastic beam is equal to the square root or some constant (k) divided by the mass density of the beam, m ,

$$\omega = \sqrt{\frac{k}{m}}$$

if this natural frequency ω is set to equal a particular natural frequency of the elastic beam under consideration, the constants k can be solved in terms of m and ω. It is therefore reasonable to assume that this k corresponds to the spring constant used in the Hartlen-Currie model. Thus the designer, knowing the mass density of the beam and its natural frequency, can solve for the value of k and use it in the Hartlen-Currie method of analysis to determine the deflection.

It should be noted, however, that the deflection determined by the Hartlen-Currie model represents the mean deflection of the beam. The designer will, of course, be interested in the maximum deflection for the analysis of the beam. Therefore, the deflection resulting from the model analysis must be modified. Through integration of mode shapes,(see Table 4), it was found that the maximum deflection of the beam would be on the order of 1.5 to 1.7 times the mean deflection. Using this information and a desire to be on the safe side, the designer should consider the maximum

deflection, w_{max}, to equal 2.0 times the mean deflection, $\bar{w}$, given by the Hartlan-Currie model analysis, i.e.,

$$w_{max} = 2\bar{w}.$$

The determination of maximum deflection for known beam loading conditions and wind forces is a simple task. Once the deflection is known the stress can easily be found. When the designer knows the maximum deflection of the beam for a given deflection curve and wind force, the stress placed on the beam by the deflection can be determined using moment-deflection relations.

The assumptions made in the above analytical method can be summarized as follows: It is first assumed that some small segment of the elastic beam being analyzed will act like the rigid beam of the Hartlen-Currie model. The remaining portions of the beam will act to provide the spring like supports used for the model analysis. Secondly, it is assumed that the damping and frequency of the small segment is similar to that of the spring supported rigid beam. Thus, the natural frequency and mass density of the elastic beam can be used to calculate a constant, k , which corresponds to the spring constants of the Hartlen-Currie model. A third assumption made is that, for calculating maximum deflection, the designer use a correction coefficient of 2 times the mean deflection resulting from the model analysis. This correction coefficient may be slightly conservative, but it gives a more accurate value of the maximum deflection needed for design calculations than the direct model analysis

results. The final assumption that has to be made is that the wind force acts uniformly on the beam.

The moment and the deflection in an elastically supported beam can be easily formed by the moment-area method. An elastically supported beam may be considered as a simply supported beam with an end moment applied on each end. It is well-known* that the maximum moment of simply-supported beam subjected to a uniform load is $\frac{1}{8} qL^2$. The slope at the end is $\frac{L}{3EI} \frac{1}{8} qL^2 = \frac{qL^3}{24EI}$. The slope due to the end moment is $M_o \frac{L}{2EI}$ The end moment M_o is yet of course unknown, but is in turn related to the slope at the end to the combined effect

$$M_o = k \frac{dv}{dx} = \frac{EI\sigma}{L} \frac{dy}{dx}$$

Thus $EI \frac{dy}{dx} = \frac{1}{24} qL^3 - EI \frac{\sigma}{2} \frac{dy}{dx}$. Solving for $\frac{dy}{dx}$ and substituting into the expression for M_o, we obtain

$$M_o = \frac{\sigma}{12(2 + \sigma)} qL^2$$

The maximum deflection is

$$w_{max} = \frac{5\ qL^4}{384EI} - M_o \frac{L^2}{8\ EI}$$

The results are tabulated in Table 3, and plotted in Figure 14.

In the application, the following data are usually given:

$$\sigma, \quad d, \quad L, \quad m, \quad \text{and} \quad \gamma .$$

It is desired to compute the flexural stress f_b.

---

*For simplicity we restricted our attention to a common case where the beam is symmetric and prismatic and is uniformly loaded.

Table 3. Deflection Moment Relationship

End Fixity Coefficient, σ	Maximum Moment* Coefficient, a	Maximum Deflection Coefficient, b	$\frac{a}{b}$
0	0.125	0.01302	9.600
0.1	0.121	0.01253	9.657
0.5	0.1083	0.01094	9.899
1	0.0972	0.00955	10.178
5	0.0655	0.00557	11.759
6	0.0625	0.00521	11.996
10	0.0695	0.00432	16.088
20	0.0758	0.00352	21.173
50	0.0801	0.00302	26.523
100	0.0817	0.00282	28.972
200	0.0825	0.00272	30.330
1000	0.0832	0.00262	31.756
10000	0.0833	0.00261	31.916
1000000	0.0833	0.00260	32.039
∞	0.0833	0.00260	32.039

* Use value of $\frac{\sigma}{12\ (2 + \sigma)}$ or $\frac{1}{8} - \frac{\sigma}{12(2 + \sigma)}$, whichever is larger.

The procedure is as follows: For given γ , one can compute the nondimensional damping $\frac{\gamma A \rho_m}{\rho_a d^2}$, from which one can determine $\bar{w}/d$, according to Hartlen-Currie model. From elementary beam theory,

$$w_{max} = \frac{bqL^4}{EI} , \qquad M = aqL^2$$

Eliminating q between them,

$$M = \frac{a}{b} E \, w_{max} \frac{I}{L^2}$$

By flexural formula,

$$f_b = \frac{M c}{I} = \frac{a}{b} E \frac{w_{max}}{2d} \left(\frac{d}{L} \right)^2$$

Noting that $\delta/2 = \bar{\delta}$, we finally obtain $w_{max}/2 = \bar{w}$

$$f_b = \frac{a}{b} E \frac{\bar{w}}{d} \left(\frac{d}{L} \right)^2$$

where a/b corresponding to a given σ can be obtained from Fig. 14.

DESIGN EXAMPLE NO.4: Using the cross section of example 1 (p.116), the mean deflection and flexural stress for a member in the subcritical regime can be calculated.

Given that the length (L) = 100 ft, end fixity $\sigma_1 = \sigma_2 = 10$, structural damping coefficient (γ) = 0.0056, and mass density of air (ρ_a) = 1.123×10^{-7} lb-sec^2/in^4

a. Mean deflection can be found from Fig. 11, p. 26
$\gamma A \rho_m / \rho_a d^2 = 5.33$; therefore, $\frac{\bar{w}}{d} = 0.09$ which means $\bar{w} = 0.0074$ inch.

b. Flexural stress can be found as follows: From Fig. 14, p.30, a/b = 16

$$f_b = \frac{a}{b} E \frac{\bar{w}}{d} \left(\frac{d}{L} \right)^2 = 16 \times 29 \times 10^6 \times 0.09 \times \left(\frac{12.217}{100 \times 12} \right)^2 = 4328 \text{ psi}$$

III. APPLICATION OF RANDOM VIBRATION THEORY TO SUPERCRITICAL FLOW CONDITION

Equation (7) in p. 109 can be wriiten as follows:

$$\text{rms } w\Big|_{x=\frac{L}{2}} = \frac{1}{16\sqrt{\pi^3}} C_L \frac{\rho_a}{\rho_m}\frac{d}{A} V^2 \, (L_1 + L_2 + L_3 + \ldots.)$$

where ρ_a = mass density of air $= \dfrac{0.075 \text{ lb/cf}}{g}$

$$\rho_m = \frac{487 \text{ lb/cf}}{g} \quad \text{(for steel)}$$

$$L_i = \frac{w_i(\frac{L}{2}) \int_o^L w_i dX}{f_i^2 \int_o^L w_i^2 \, dX} \sqrt{\frac{S_f(St_i)St_i}{\delta_i/2\pi}}$$

where γ_i is substituted by $\delta_i / 2\pi$.

For design purposes, we shall assume $\delta_i = \delta$ = constant.

Now, for symmetric beams, $L_2 = 0$, and the product of

$$\frac{w_i(\frac{L}{2})}{K_i} \quad \text{and} \quad \frac{\int_o^L w_i \, dX}{K_i} \quad \left(\text{where } K_i = \sqrt{\int_o^L w_i^2 \, dX}\right)$$

can be found in Table 4. It is observed that each is virtually independent of σ and P. Thus, the products are slightly less than 1.4 and 0.5 for i = 1 and i = 3, respectively.

We observe that,

$$\frac{L_3}{L_1} = \left(\frac{f_1}{f_3}\right)^2 \sqrt{\frac{S_f(St_3)St_3}{S_f(St_1)St_1}} \cdot \frac{0.5}{1.4}$$

in which, the values of S_f can be obtained from Figs. 12 and 13. It is noted that $S_f(St_3)/S_f(St_1)$ and St_3/St_1 are approximately 0.2 and 3, respectively. Thus for $f_1/f_3 < 0.2$, $\frac{L_3}{L_1} < 1\%$.

Table 4 Mean and RMS Deflection
First Mode (n=1)

$\sigma_1 = \sigma_2$	$\sqrt{P}$	$\bar{w}_1 / K_1$	$w_1(\frac{L}{2}) / K_1$
0	0.0	.90	1.4
	7.7746	.90	1.4
	10.9545	.90	1.4
5	0.0	.88	1.5
	7.7746	.89	1.5
	10.9545	.89	1.4
10	0.0	.87	1.5
	7.7746	.88	1.5
	10.9545	.88	1.5
20	0.0	.86	1.5
	7.7746	.87	1.5
	10.9545	.87	1.5
100	0.0	.84	1.6
	7.7746	.85	1.5
	10.9545	.86	1.5

Table 4 (Con't) Mean and RMS Deflection
Second Mode (n=2)

$\sigma_1 = \sigma_2$	$\sqrt{P}$	$\bar{w}_2/K_2$	$w_2(\frac{L}{2})/K_2$
0	0.0	0	0
	7.7746	0	0
	10.9545	0	0
5	0.0	0	0
	7.7746	0	0
	10.9545	0	0
10	0.0	0	0
	7.7746	0	0
	10.9545	0	0
20	0.0	0	0
	7.7746	0	0
	10.9545	0	0
100	0.0	0	0
	7.7746	0	0
	10.9545	0	0

Table 4 (Con't) Mean and RMS Deflection
Third Mode (n=3)

$\sigma_1 = \sigma_2$	$\sqrt{P}$	$\mathbb{I}(w_3)/K_3$	$w_3(\frac{L}{2})/K_3$
0	0.0	.30	- 1.4
	7.7746	.30	- 1.4
	10.9545	.30	- 1.4
5	0.0	.33	- 1.4
	7.7746	.32	- 1.4
	10.9545	.31	- 1.4
10	0.0	.35	- 1.4
	7.7746	.33	- 1.4
	10.9545	.32	- 1.4
20	0.0	.36	- 1.4
	7.7746	.34	- 1.4
	10.9545	.33	- 1.4
100	0.0	.37	- 1.4
	7.7746	.34	- 1.4
	10.9545	.33	- 1.4

Where $\mathbb{I}(w_n) = \int_0^L w_n dX$

$n = 1, 2, 3.$

$K_n = \left(\int_0^L w_n^2 dX \right)^{\frac{1}{2}}$

Then L_3 is less than 1% of L_1 and L_1 should represent at least 95% of $\sum_{i=1,3}^{\infty} L_i$. Under this circumstance,

$$\frac{\text{rms } w}{d} = 2.445 \times 10^{-6} \frac{V^2}{Af_1^2} C_L \frac{w_1 \left(\frac{L}{2}\right)}{K_1} \frac{I(w_1)}{K_1} \cdot \sqrt{\frac{Sf(St_1)St_1}{\delta_1/\pi}}$$

where $I(w_1)$ denotes $\int_0^L w_1 dX$,

$$= 3.1 \times 10^{-6} \frac{V^2}{Af_1}^2 C_L \sqrt{\frac{Sf\ (St_1)\ St_1}{\delta_1/\pi}}$$

DESIGN EXAMPLE NO. 5

This example is a continuation of example No. 3. Here the member shall be checked for random vibration. Example No. 3 showed that the Reynolds number for the first mode of vibration in bending fell within the transitional range of 1.0×10^5 to 4.0×10^5 as indicated in available literature (see Fig. 17 p. 47 and Fig 19 p. 50). Both references deal with circular cross sections*, and so an analysis shall be made on the member of example No. 3.

Beam properties are listed on p. 123. 12" ϕ standard weight pipe. Both ends are simply supported ($\sigma_1 = \sigma_2 = 0$)

Length = 40 Feet Tensile Stress = 35ksi

Independent Lift Coefficient $C_L = 1.2$

Logarithmic Decrement $\delta_1 = \delta_2 = 0.02$

From example No. 3 the velocity corresponding to the first mode of vibration in bending is 33.10 mph which equals 582.57 in/sec. The actual frequencies of vibration for the first three modes of vibration can easily be calculated knowing the values of $\sqrt[4]{Q}$ from the following relationship:

$$P_n = \sqrt{\frac{\Omega^4 EI}{\rho_m A L^4}}$$

Where P_n = Frequency (Radians/Sec) n = 1, 2, 3

$\Omega = \sqrt[4]{Q}$

ρ_m = Mass Density

*Note: The Reynolds numbers for HP sections of examples 1 & 2 also fall above the 1.0×10^5 zone limit however, no literature is available to indicate that cross sections other than circular ones reach supercritical vibrations. If it is found that structural shapes do infact reach a supercritical range then the method outlined in this example should be used to check flexural stress due to random vibration.

Thus for this example

$$P_1 = 57.42 \text{ Rad/Sec}$$

$$P_2 = 172.02 \text{ Rad/Sec}$$

$$P_3 = 358.90 \text{ Rad/Sec}$$

These frequencies can now be used to find the normalized power spectrum $S_f(St_n)$ which is a function of the resonant Strouhal number*

$$St_n = \frac{P_n\, d}{2\pi V_1}$$

Therefore St_1 & St_3 can be used to find $S_f(St_1)$ and $S_f(St_3)$ on Fig. 12 p.27 .

$$St_1 = 0.200 \qquad S_f(St_1) = 1.3$$

$$St_3 = 1.250 \qquad S_f(St_3) = 0.1$$

From Table 4

$$\frac{w_1(L/2)}{K_1} = 1.4$$

$$\frac{w_3(L/2)}{K_1} = -1.4$$

$$\int_0^L \frac{w_1}{K_1}\, dx = 0.90$$

$$\int_0^L \frac{w_3}{K_3}\, dx = 0.30$$

---

*Note: Since the Reynolds number is within the transitional range the vibration could become harmonic, that is, the wind velocity for the 1st mode excites vibration in the third mode. Therefore for random vibrations Strouhal numbers must be calculated for the 1st and 3rd modes using the velocity of the 1st mode.

With the above information the root mean square deflections of the member at midspan can be calculated using the formula presented on p. 136 as follows:

For n = 1:

$$\text{rms } w\Big|_{x = L/2} = (2.445 \times 10^{-6})(1.2)\,\frac{(582.57 \text{ in/sec})^2}{(14.6 \text{ in}^2)\left(\frac{57.42 \text{ rad/sec}}{2\pi}\right)^2} \cdot (12.75 \text{ in})(1.4)(0.9)\sqrt{\frac{(1.3)(0.20)}{(0.02/\pi)}}$$

$$= 0.084 \text{ in}$$

For n = 3

$$\text{rms } w\Big|_{x = L/2} = (2.445 \times 10^{-6})(1.2)\,\frac{(582.57 \text{ in/sec})^2}{(14.6 \text{ in}^2)\left(\frac{358.90 \text{ rad/sec}}{2\pi}\right)^2} \cdot (12.75 \text{ in})(-1.4)(0.30)\sqrt{\frac{(0.1)(1.25)}{(0.02)/\pi}}$$

$$= -4.96 \times 10^{-4} \text{ in}$$

So from the above it can be seen that the deflection of the member due to resonant vibration action tends to reduce the principal deflection due to the natural vibration at the first mode by 0.6%, a negligible amount for this example. The actual midspan deflection is then:

$$\bar{w} = (8.4 \times 10^{-2} \text{ in}) - (4.96 \times 10^{-4} \text{ in}) = 8.35 \times 10^{-2} \text{ in}$$

The bending stress (f_b) for this deflection can easily be calculated as:

$$f_b = \frac{a}{b} E \frac{\bar{w}}{d} \left(\frac{d}{L}\right)^2$$

where: $\frac{a}{b}$ can be read from Table 3 p. 134 or found in Figure 14 p. 31 (For $\sigma_1 = \sigma_2 = 0$ a/b = 9.6)

So: $$f_b = (9.6)(29 \times 10^6 \text{ lb/in}^{-2})\,\frac{(8.35 \times 10^{-2} \text{ in})}{(12.75 \text{ in})}\left(\frac{(12.75 \text{ in})}{(40 \text{ ft})(12 \text{ in/ft})}\right)^2$$

$$= 1.286 \times 10^3 \text{ lb/in}^2 = 1.286 \text{ ksi}$$

It is interesting to compute f_b by using the relation:

$$\text{Bending Moment } (M) = -EI \left. \frac{\partial^2 w}{\partial x^2} \right|_{x = \frac{L}{2}}$$

Since w = Sin x it follows that:

$$\left. \frac{\partial^2 w}{\partial x^2} \right|_{x = \frac{L}{2}} = \frac{-\pi^2}{L^2} \bar{w}$$

and

$$M = EI \frac{\pi^2}{L^2} \bar{w}$$

$$= (29 \times 10^6 \text{ lb/in}^2)(279 \text{ in}^4) \left[\frac{\pi}{(40 \text{ ft})(12 \text{ in/ft})} \right]^2 (8.35 \times 10^{-2} \text{ in})$$

$$= 2.894 \times 10^4 \text{ in lbs}$$

and $f_b = \frac{Mc}{I} = \frac{(2.894 \times 10^4 \text{ in lbs})(12.75 \text{ in})}{(279 \text{ in}^4)(2)} = 6.613 \times 10^2 \text{ psi}$

At peak frequency $f_b = (2)(6.613 \times 10^2 \text{ psi}) = 1.3 \times 10^3 \text{ psi}$

which checks with the previous calculation of f_b.

With this knowledge the designer now has a complete picture of how the chosen section will react under existing winds. A sound decision can therefore be made as to whether to use the given member as it is, modify it to alter detrimental vortex shedding patterns, or choose a new section for analysis.

PART D
BIBLIOGRAPHY

The main approach to search for relevant literature on flow-induced vibrations is as follows:

1. Personal Collections

Dr. Nicholas Basdekas, is a specialist in this area, and has been interested in this subject for two decades. In his professional activities, he has maintained contact with a large number of researchers in this field. He has kindly loaned us his personal collection of thirty articles in this area.

Dr. Chris Yiu of Pavlo Engineering Co. of New York, is currently the Chairman of Subcommittee on Cable Stayed Bridges in the ASCE Structural Division. His Committee is the clearinghouse of information on the cable stayed bridges and has recently produced a draft copy of bibliography on Cable Stayed Steel Bridges. In this collection, it contains 13 papers on aerodynamic behavior of cable stayed bridges and 12 papers on behavior of cables.

2. Library Search

Chi Associates has access to the facility of computerized literature search. The following sources were scanned for the period covered in parathesis:

* National Technical Information Service (1964-1975)

* Engineering Index (1970-1975)

* Defense Document Center - Unclassified Reports (1966-1975)

* INSPEC-MECH ENGR (1973-1975)

The following key words were used:

* Strouhal

* Strumming

* Vortex Shedding

* Vortex Street

* von Karman Street

* Flow Induced Vibrations

The number of hits scored in each key word for each source was recorded,and all hits were identified in terms of the titles of the articles or report and the abstracts, if available. Through the review of the titles and abstracts, a decision was made which of these articles or reports should be acquired for closer examination. All articles processed this way are listed in alphabetical order of the first author's names.

SHOCK AND VIBRATION INFORMATION CENTER
Naval Research Laboratory
Washington, D.C. 20390
Tel. 202 767 2220

13 August 1975 8404:162:RHV:bgs

Dr. Michael Chi
2721 24th Street North
Arlington, VA 22207

Dear Dr. Chi:

This is reply to your request for information about the Strouhal number for structural shapes. A search of the Shock and Vibration Information Center's data base was performed using the following key words or the combination of key words:

Vortex Shedding
Vortex Noise
Vortex Induced Excitation
Structural Forms
Structural Members

No references to reports that would contain values of the Strouhal number for structural shapes were found in this search. The Shock and Vibration Information Center's data base contains references to many technical papers and unclassified unlimited technical reports that have been published since 1969.

We did find a reference to the range of Strouhal numbers in a paper by Scanlan and Wardlaw in the following reference:

Scanlan, R.H. and Wardlaw, R.L., Reduction of Flow-Induced Structural Vibrations, Proceedings of Colloquium on Isolation of Mechanical Vibration, Impact, and Noise, (AMD-1), presented at the Design Engineering Technical Conference, Cincinnati, Oh, September 1973, p 41.

Very truly yours,

R. H. Volin

Rudolph H. Volin

LEADING ARTICLES

Principal Review Articles:

Morris, A. W., "A Review on Vortex Streets, Periodic Wakes and Induced Vibration Phenomena," J. of Basic Engineering, Trans. ASME, (June, 1964), pp. 185-196.

Berger, E., and Wille, R., "Periodic Flow Phenomena," Annual Review of Fluid Mechanics, Vol. 4., 1972.

"Wind Forces on Structures," Final Report of Task Committee on Wind Forces, Trans. ASCE, Vol. 126, Part II, 1961, pp. 1124-1197.

Diggs, J. S., "A Survey of Vortex Shedding from Circular Cylinders with Applications Toward Towed Arrays," Report by MAR, Inc. to NSRDC, Cardarock, Maryland, 1974.

Wille, R., "Kármán Vortex Streets," Advances in Applied Mechanics VI, Academic Press, New York, 1960.

Wille, R., "On Steady Flows and Transient Motions," Progress in Aeronautical Sciences, Vol. 7, Pergamon Press, New York, 1966.

Morkovin, M. V., "Flow Around Fully Separated Flows," ASME Symposium on Fully Separated Flows, 1964.

Annotated Bibliography:

Mulcahy, T. M., and Chen, S. S., Annotated Bibliography on Flow Induced Vibrations, Argonne National Lab. Tech. Memo. ANL-CT-74-05.

Symposia and Books:

The Modern Design of Wind-Sensitive Structures, CIRIA Publication, Proc. of the Seminar held on June 18, 1970, at ICE London.

Proceedings of International Symposium on Vibrational Problems in Industry, 1971.

Sachs, P., Wind Forces in Engineering, Pergamon Press, New York, 1972.

Flow-Induced Structural Vibrations, IUTAM-IAHR Symposium, Karlsruhe, E. Naudascher (Ed), Springer-Verlag, New York, 1972.

Proc. of the Third International Conference on Wind Effects on Buildings and Structures, Tokyo, Saidon Co., Tokyo, 1971.

ASME Symposium on Fully Separated Flows, 1964.

Mair, W. A., and Maull, D. J., "Bluff Bodies and Vortex Shedding - A Report on Euromech 77, J. Fluid Mech., Vol. 45, Part 2, 1971, pp. 209-224.

BIBLIOGRAPHY

1. A summarized account of the Severn Bridge Aerodynamic Investigation, NPL /Aero/ 222, H.M.S.O. 1952.

2. Abernathy, F.H., "Flow over an Inclined Plate", J. Basic Engineering Trans. ASME. Ser. D, Vol. 84, 1962, pp. 380.

3. Abernathy, F.H., and Kronauer, R.E., "The Formation of Vortex Streets", Journal of Fluid Mechanics, Vol. 13, 1962, pp. 1-20.

4. Abramson, H.N., and Nevill, G.E., "Some Modern Developments in the Application of Scale Models in Dynamic Testing", Use of Models and Scaling in Shock and Vibration, ASME, 1963.

5. Achenbach, E., "Influence of Surface Roughness on the Cross-Flow around a Circular Cylinder", J. Fluid Mech., Vol. 46, 1971, pp. 321-335.

6. Achenbach, E., "Distribution of Local Pressure and Skin Friction around a Circular Cylinder in Cross-Flow up to $Re=5 \times 10^6$", J. Fluid Mechanics, Vol. 34, Part 4, 1968, pp. 625-639.

7. Ackeret, J., "Der Winddruck auf Schornsteine mit Kreisquerschnitt", Schweiz Bauzeitung, Vol. 108, 1936, pp. 25.

8. Acrivos, A., Snowden, D.D., Grove, A.S., and Petersen, E.E., "The Steady Separated Flow past a Circular Cylinder at Large Reynolds Numbers", J. Fluid Mech., Vol. 21, Part 4, 1965, pp. 737-760.

9. Alexander, A.J., "A Theory for the Oscillating Lift on a Circular Cylinder", Symposium on Wind Effects on Buildings and Structures, Paper No. 19, Loughborough University of Technology, National Physical Laboratory and Royal Aeronautical Society, 1968.

10. Allen, H.J., and Vincent, W.G., "Wall Interference in a Two Dimensional-Flow Wind Tunnel, with Consideration of the Effect of Compressibility", Nat. Adv. Comm. Aero. Wash. Rep., 782, 1944.

11. Alton, J., "Masts and Guys under Wind Action", Canadian Eng. J., 1951, pp. 1069.

12. American National Standards Institute: "Building Code Requirements for Miniumum Design Loads in Buildings and Other Structures", New York, 1972.

13. An Investigation of the Aerodynamic Stability of the Towers Proposed for the River Severn Suspension Bridge, NPL/Aero/ 1052, H.M.S.O., 1963.

14. Anand, G.V., "Non-Linear Resonance in Stretched Strings with Viscous Damping", Journal of the Acoustical Society of America, Vol, 40, No. 6, 1966.

15. Ang, A. H-S., and Amin, M., "Formulation of Wind-Resistant Design Based on Acceptable Risk", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, III, 12, September, 1971. 10pp.

16. Angrilli, F., Disilvio, G., and Zanardo, A., "Hydro-elasticity Study of Circular Cylinders in a Water Stream", Flow-Induced Structural Vibrations, E. Naudascher,ed., Springer-Verlag, Berlin, 1974, pp. 504-512.

17. Apelt, C.J., West, G.S., and Szewczyk, A.A., "The Effects of Wake Splitter Plates on the Flow Past a Circular Cylinder in the Range $10^4<R<5 \times 10^4$", J. Fluid Mech., Vol. 61, Part 1, 1973, pp. 187-198.

18. Armitt, J., Counihan, J., Milborrow, D.J., and Richards, D.J.W., C.E.R.I., Laboratory Report, No. RD/L/R/1430, 1967.

19. Armitt, J., "Wind Effects on Buildings and Structures", Proc. Symp., Loughborough University of Technology, Loughborough, 1968.

20. Armitt, J., "Vibration of Cooling Towers", Proc. International Symposium Vibration Problems in Industry, Keswick, England, Paper No. 311, April, 1973.

21. Armitt, J., "The Effect of Surface Roughness and Free Stream Turbulence on the Flow around a Model Cooling Tower at Critical Reynolds Numbers", Proceedings of Symposium on Wind Effects on Buildings and Structures, Loughborough University of Technology, Loughborough, England, April, 1968, pp. 6.1-6.13.

22. Arnstein, K., and Klemperer, W., "Wind Pressures on the Akron Airship Dock", Journal of the Aeronautical Sciences, Vol. 3, 1936, pp. 88.

23. Ashley, H., and McIntosh,S.C.,Jr., "Application of Aero-elastic Constraints in Structural Optimization", Proceedings of the Twelfth International Congress of Applied Mechanics, Stanford University, August, 1968.

24. Atkins, W.S., and Partners, "When are Dynamic Wind Loads Important?". Unpublished Design Memorandum, 1969.

25. van Atta, C.W., "Experiments on Vortex Shedding from Yawed Circular Cylinders", AIAA J., Vol. 6, No. 5, May 1968, pp. 931-933.

26. Attri, N.S., "Energy Relationship for D-Section Galloping Conductors", Proc. Conf. Conductor Galloping, Hydroelectric Power Commission, Toronto, Canada, 1966, pp. 89-120.

27. Bailey, A., "Wind Pressure on Buildings", Journal Inst. Div. Engrs., Select. Engrg. Paper No. 189, 1933.

28. Bailey, A., and Vincent, N.D.G., "Wind Pressure on Buildings Including Effects of Adjacent Buildings", Journal Inst. Civ. Engrs., Vol. 20, No. 8, October, 1943, pp. 243-275.

29. Baines, W.D., "Effects of Velocity Distribution on Wind Loads and Flow Patterns on Buildings", N.P.L. Symposium, Paper 6, H.M.S.O. 1965.

30. Baird, R.C., "Wind-Induced Vibrations of a Pipe-Line Suspension Bridge and Its Cure", Transactions, ASME, Vol. 77, No. 6, August, 1955, pp. 797-804.

31. Bairstow, L., Applied Aerodynamics, Longmans, Green & Co., 2nd ed., 1939.

32. Baker, R., "The Fourth Bridge", Engineering, Vol. 38, August 1884, pp. 213.

33. Baker, J.F., and Willaims, E.F., "The Effect of Wind Loads on Frames with Semi-Rigid Connections", Final Report, Steel Struct. Res. Comm., London, England, 1936.

34. Bamber, D., "The Design of Towers, Masts and Pylons", DATA, Richmond, Surrey, 1957.

35. Barad, M.L., (ed.), "Project Pairie Grass-A Field Program in Diffusion", Geophysical Research Paper 59, Geophysical Research Directorate, Bedford, Mass., 1952.

36. el Baroudi, M.Y., "Measurement of Two Point Correlation of Velocity near a Circular Cylinder Shedding a Karman Vortex Street", U.T.I.A. Tech. Note 31, 1960.

37. Barray, A., "Action of Sleet on the Conductors of Overhead Lines", C.I.G.R.E., Vol. VIII, No. 207, 1935.

38. Basile, D., Faure, J., and Ohlmer, E., "Experimental Study on the Vibration of Various Fuel Rod Models in Parallel Flow", Nuclear Engineering and Design, Vol 7, 1968, pp. 517-534.

39. Bate, E., "The Vibration of Transmission Conductors", Trans. Inst. Engr., Australia, Vol. 11, 1930, pp. 207.

40. Batham, J.P., "Pressure Distributions on Circular Cylinders at Critical Reynolds Numbers", J. Fluid Mech., Vol. 57, Part 2, 1973, pp. 209-228.

41. Bearman, P.W., "Investigation of the Flow behind a Two-Dimensional Model with Blunt Trailing Edge and Fitted with Splitter Plates", Journal of Fluid Mechanics, Vol. 21, Part 2, 1965, pp. 241-255.

42. Bearman, P.W., "An Investigation of the Forces on Flat Plates Normal to a Turbulent Flow", J. Fluid Mech., Vol. 46, Part 1, 1971, pp. 177-198.

43. Bearman, P.W., "On Vortex Street Wakes", J. Fluid Mech., Vol. 28, No. 4, 1967, pp. 625-641.

44. Bearman, P.W., "The Effect of Base Bleed on the Flow behind a Two-Dimensional Model with a Blunt Trailing Edge", Aero. Quart., Vol. 8, 1967, pp. 207-224.

45. Bearman, P.W., "Wind Loads on Structures in Turbulent Flow", Preprints to CIRIA Seminar on the Modern Design of Wind-Sensitive Structures (London) Paper 4, June 1970, 7pp.

46. Bearman, P.W., "The Flow around a Circular Cylinder in the Critical Reynolds Number Regime", NPL Aero. Rep., 1257, Vol. 28, 1968.

47. Bearman, P.W., "Fluctuating Forces on Bluff Bodies in Turbulent Flow", Proceedings of Conference on the Aerodynamics of Atomospheric Shear Flows, No. 48, Munich Germany, 1969, pp. 24.1-14.13.

48. Bearman, P.W., "On Vortex Shedding from a Circular Cylinder in the Critical Reynolds Number Regime", J. Fluid Mech., Vol. 37, No. 3, 1969, pp. 577-585.

49. Bearman, P.W., "Turbulence-Induced Vibrations of Bluff Bodies", IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper H1, August, 1972.

50. Bearman, P.W., and Trueman, D.M., "An Investigation of the Flow around Rectangular Cylinders". The Aero Quart., Vol. 23, 1972, pp. 229-237.

51. Bearman, P.W., and Wadcock, A.J., "The Interaction Between a Pair of Circular Cylinders Normal to a Stream", Journal of Fluid Mechanics, Vol. 61, 1973, pp. 499-511.

52. Beavers, G.S. and Plunkett, R., "Modeling of Flow-Induced Vibrations in Heat Exchangers and Nuclear Reactors", Trans. of ASME, December, 1974, pp. 358-364.

53. Beavers, G.S., Sparrow, E.M., and Lloyd, J.R., "Low Reynolds Number Turbulent Flow in Large Aspect Ratio Rectangular Ducts", Journal of Basic Engineering, Trans., ASME, Series D, Vol. 93, No. 2, 1971, pp.296-299.

54. Beliveau, J.G., Vaicaitis, R., and Shinozuka, M., Random Motions of a Suspension Bridge Subjected to Buffeting and Self-Excited Wind Loads, Tech. Rept. No. 4 (NSF-GK-37271X) Dept. of Civil Engr., Columbia University N.Y., January, 1975.

55. Benny, D.J., "A Non-Linear Theory for Oscillations in a Parallel Flow", Journal of Fluid Mechanics, Vol. 10, 1961, pp. 209.

56. Benny, D.J., and Lin, C.C., "On the Secondary Motion Induced by Oscillations in a Shear Flow", Phys. Fluids, Vol. 4, 1960, pp. 656.

57. Berger, E.W., "Unterdruckung des Turbulenzeinsatzes der Karmanschen Wirbelstrasse im Nachlauf von Kreiszlindern Durch Gesterute Querschungungen des Erzeugenden Zylinders im Ubergangsbereich Oberhalf Re= 160", Jahrbuch der wiss. Ges., L & R, Berlin, 1964.

58. Berger, E., and Wille, R., "Periodic Flow Phenomena", Annual Review of Fluid Mechanics, Vol. 4, 1972, pp. 313-340.

59. Berger, E.W., "Die Bestimmung der Hydrodynamischen Grossen einer Karmanischen Wirbelstrasse aus Hitzderhtmessungen bei kleinen Reynoldsschen Zahlen", Zeitschrift fur Flugwissenschaften, Vol. 12, 1969, pp. 41-59.

60. Berger, E.W., "Unterdruckung der laminaren Wirbelstromung und des Turbulenzeinsatzes der Karmanschen Wirbelstrasse im Nachlauf eines schwingenden Zylinders bei Kleinen Reynolds Zahlen", Jahr. Wiss. Ges., L & R, Berlin, 1964, pp. 164-172.

61. Berger, E.W., "Suppression of Vortex Shedding and Turbulence behind Oscillating Cylinders", Physics of Fluids, Vol. 10, No. 9, Part 2, 1967, pp. S191-193.

62. Berger, E.W., and Willie, R., "Periodic Flow Phenomena", Annual Review of Fluid Mechanics, Palo Alto, Annual Reviews Inc., 1972, pp. 313-340.

63. Bergh, H., and van den Berg, B., "On the Visualization of Laminar Boundary Layer Oscillations and the Transition of Turbulent Flow", Zeitf. Angew. Math and Physik, Vol. 9B, 1958, pp. 97.

64. Betchov, R., "Simplified Analysis of Boundary Layer Oscillations", J. of Ship Research, Vol. 4, 1960, pp. 37.

65. Betchov, R., and Criminale, W.O., Stability of Parallel Flows, Academic Press, New York, 1967.

66. Betchov, R., and Szewezyk, A., "Stability of a Shear Layer between Parallel Streams", Physics of Fluids, Vol. 6, 1963, pp. 1391.

67. Biggs, J.M., "Wind Loads on Truss Bridges", Transactions, ASCE, Vol. 119, 1954, pp. 879.

68. Biggs, J.M., Namyet, S., and Adachi, J., "Wind Loads on Girder Bridges", Transactions, ASCE, Vol. 121, 1956, pp. 101.

69. Binder, R.C., "The Flutter or Galloping of Certain Structures in a Fluid Stream". Shock and Vibration Bulletin, Vol. 39, Part 3, January, 1969.

70. Bingham, H.H., Weimer, D.K., and Griffin, W., "The Cylinder and Semicylinder in Subsonic Flow", Princeton Univ. Dept. Phys. Tech. Rept. 11-13, July, 1952.

71. Bingham, H.H., Weimer, D.K., and Griffith, W., The Cylinder and the Semicylinder in Subsonic Flow, Princeton Univ., Dept. of Physics, Tech. Report 11-13, 1952.

72. Birkhoff, G., "Formation of Vortex Streets", Journal of Applied Physics, No. 24, 1953, pp. 98-103.

73. Birkhoff, G., "A New Theory of Vortex Streets", Proceedings of the National Academy of Sciences, No. 38, 1952, pp. 409-410.

74. Birkhoff, G., and Zarantanello, E., Jet, Wakes, and Cavities, New York Academic Press, 1957, pp. 291-292.

75. Biron, F., "L'Action du Vent Sur Les Constructions", Science et Indust, Constr., Vol. 18, No. 16, 1934, pp. 131.

76. Birse, R.D., "The Changes of Tension in Galloping Conductor", R.D. Rept. No. 68-502-H, Hydroelectric Power Commission, Toronto, Canada, 1968.

77. Bishop, R.E.D., and Hassan, A.T., "The Lift and Drag Force on a Cylinder in a Flowing Fluid", Proceedings, Royal Society, London, Series A, Vol. 277, 1964, pp. 32-50.

78. Bisplinghoff, R.L., Ashley, R.L., and Halfman, R.L., Aeroelasticity, Addison-Wesley Publishing Co., 1957.

79. Bixby, W.H., "Wind Pressures in Engineering Construction", Engineering News, Vol. 33, 1895, pp. 174-184.

80. Bjerkness, V., Bjerkness, J., Solberg, H., and Bergeron, T., Physikalische Hydrodynamik, Berlin, 1933.

81. Blackadar, A.K., "The Vertical Distribution of Wind and Turbulent Exchange in a Neutral Atmosphers,: Journal of Geophysical Research, Vol. 67, 1962, pp. 3095-3102.

82. Blackiston, H.S., "Tip Effects on Fluctuating Air Loads on a Circular Cylinder Perpendicular to an Air Flow", AIAA Fifth Annual Structures and Materials Conference, Palm Springs, April, 1964.

83. Blackman, R.B., and Tukey, J.W., The Measurement of Power Spectra, New York, Dover, 1958.

84. Blanjeau, L., "L'Action du vent sur les Constructions", Ossature Metallique, No. 2, February, 1949.

85. Blankson, I., and Finston, M., "Summary of Experimental Studies on Oscillating Cables", M.I.T. Aerophysics Lab. T.R. 151, April, 1969.

86. Bleich, F., "Dynamic Instability of Truss-Stiffened Suspension Bridges under Wind Action", Trans. A.S.C.E., Vol. 114, 1949, pp. 1177.

87. Bleich, F., McCullough, C.B., Rosecrans, R., and Vincent, G.S., "The Mathematical Theory of Vibration in Suspension Bridges", Bur. of Pub. Rds. Rept., 1950.

88. Blenk, H., Fuchs, D., and Liebers, F., "Uber Messungen von Wirbelfrequenzen", Luftfahrtforschung, Vol. 12, 1935, pp. 38.

89. Blessmann, J., Damage Caused by the Wind, Federal Univ. of Rio Grande do Sul, Porto Alegre, Structural Engineering Series 2, July, 1971, 35pp.

90. Blevins, R., "Vortex Induced Vibration of Bare and Ribbon Cables", NSRDC, Unpublished (MAR 644), September, 1971.

91. Blevins, R., "A Hydroacoustic Analysis of Cable Strumming", NSRDC, Unpublished (MAR 566), December, 1971.

92. Blevins, R., "Flow-Induced Vibration of Bluff Structures", Ph.D. Thesis, California Institute of Technology, 1974.

93. Blevins, R., and Burton, T.E., "Fluid Forces Induced by Vortex Shedding", General Atomic Company Report, GA-A13031, 1974.

94. Bloor, M.S., "The Transition to Turbulence in the Wake of a Circular Cylinder", Journal of Fluid Mechanics, Vol. 19, Part 2, 1964, pp. 290-304.

95. Bloor, M., and Gerrard, J.H., "Measurements of Turbulent Vortices in a Cylinder Wake", Proceedings of the Royal Society, Series A., Vol. 294, 1966, pp. 319-394.

96. Bohne, Q.R., "Ground Wind Induced Loads on Axisymmetric Launch Vehicles", AIAA Fifth Annual Structures and Materials Conf., Palm Springs, April, 1964.

97. Boltz, F.W., Kenyon, G.C., and Allen, C.Q., "The Boundary-Layer Transition Characteristics of Two Bodies of Revolution, a Flat Plate, and an Unswept Wing in a Low-Turbulence Wind Tunnel", NASA Tech. Note D-309, 1960.

98. Bonner, W.D., "Statistical and Kinematical Properties of the Low-Level Jet Stream". Statellite and Meso-meterorology Research Project, Paper 38, Department of Geophysical Sciences, University of Chicago, Chicago, Ill., 1965, pp. 54.

99. Borden, A., Young, D.B., and Ellsworth, W.M., Jr., "Hydrodynamic Induced Vibrations of Cylinders Towed in Various Combinations", David Taylor Model Basin Report C-452, 1951.

100. Borges, A.R.J., "Vortex Shedding Frequencies on the Flow Through Two-row Banks of Tubes", Journal of Mechanical Engineering Science, Vol. 11, No. 5, 1969, pp. 498-502.

101. Borgoliubov, N.N., and Mitropolosky, Y.A., Asymptotic Methods in the Theory of Non-linear Oscillation, Hindustan Publishing Corporation, 1961.

102. Bostaock, B.R., and Mair, W.A., "Pressure Distributions and Forces on Rectangular and D-Shaped Cylinders", Aero Quarterly, 1-6 , February, 1972.

103. Boyer, D.L., "Flow Past Right Circular Cylinder in a Rotating Frame", J. Basic Eng., Vol. 92, 1970, pp. 430.

104. Bradbury, L.J.S., The Structures of a Self-Preserving Turbulent Plant Jet", J. of Fluid Mechanics, Vol. 23-31, 1965.

105. Brekke, G.N., "Wind Pressures in Various Areas of the United States". Building Materials and Structures Report, 152, Nat. Bur. of Standards, April, 1959, pp. 4 &7.

106. Breslin, J.P., "Dynamic Forces Exerted by Oscillating Cables", J. Hydronautics, Vol. 8, No. 1, January, 1974, pp. 19-31.

107. Briggs, L.J., and Dryden, H.L., "Aerodynamics ", International Critical Tables, Vol. i, 1926, pp. 402-411.

108. Brodetsky, S., "Discontinuous Fluid Motion Past Circular and Elliptic Cylinders", Proc. Roy. Soc., London, Ser. A., Vol. 102, No. 718, February, 1923, pp. 542-553.

109. Brooks, N.P.H., "Experimental Investigation of the Aeroelastic Instability of Bluff Two-Dimensional Cylinders", M.A.Sc. Thesis, University of British Columbia, 1960.

110. Browand, F.K., "An Experimental Investigation of the Instability of an Incompressible, Separated Shear Layer", Journal of Fluid Mechanics, 1966, pp. 281-309.

111. Brown, G.B., "On Vortex Motion in Gaseous Jets and the Origin of Their Sensitivity to Sound", Proc. Phys. Soc., Vol. 47, 1935, pp. 703.

112. Brown, F.N.M., "The Organized Boundary Layer", Proc. 6th Midwestern Conf. on Fluid Mech., Printing Div., Univ. of Texas, September, 1959.

113. Brown, F.N.M., "Some Characteristics of the Periodic Vortical Elements within the Transitioning Boundary Layer", Univ. Notre Dame, Aero. Eng. Rept., February, 1960.

114. Bryson, A.E., "Symmetric Vortex Separation on Circular Cylinders and Cones", J. Appl. Mech. Trans, ASME, Ser. E., Vol. 26, 1959, pp. 643.

115. Bublitz, P., "Measurements of the Unsteady Pressure and Forces Acting Upon an Oscillating Cylinder", IUTAM/IAH R Symposium on Flow-Induced Structural Vibrations, Karlscruhe, Germany, Paper F1, August, 1972.

116. Buckland, P.G., and Wardlaw, R.L., "Some Aerodynamic Considerations in Bridge Design", Engineering Journal, April, 1972, 7 pp.

117. Bursnall, W.J., and Loftin, L.K., "Experimental Investigation of Localized Regions of Laminar Boundary Layer Separation", Nat. Adv. Comm. Aero. Wash., Tech. Note 2338, 1951.

118. Cain. T.H., Kelling, F.H., and Linn, W.L., "Results of Aerodynamic Tests on Sectional Models of Arch Suspended Road Bridge", Proc. International Symp. on Vibration Problems in Industry, Teddington, Keswick, England, Paper No. 322, April, 1973, 15 pp.

119. Caldwell, D.R., and van Atta., C.W., "Some Measurements Of Instabilities in Edman Boundary Layers" Proceedings of AGARD Conference on Aerodynamics of Atmospheric Shear Flows, No. 42, 1969, pp. 22.1-22.13.

120. Caldwell, D.R., and van Atta, C.E., "Ekman Boundary Layer Instabilities", Journal of Fluid Mechanics, Vol. 44, Part 1, October, 1970, pp. 79-95.

121. Carroll, J.S., "Laboratory Studies of Conductor Vibrations", Transactions, AIEE, Vol. 55, 1936, pp. 543.

122. Castenheta, M.N., "Dynamic Behaviour of Overhead Power Lines Subject to the Action of the Wind", CIGRE Paper 22-08, August, 1970, 15 pp.

123. Cermak. J. E., "Applications of Fluid Mechanics to Wind Engineering---A Freeman Scholar Lecture", Journal of Fluids Engineering, March, 1975, pp. 9-33.

124. Cermak, J.E., "Separation-Induced Pressure Fluctuations on Buildings", Proceedings of Seminar on Wind Loads on Structures, University of Hawaii, Honolulu, Hawaii, October, 1970, pp. 55-70.

125. Cermak, J.E., "Determination of Wind Loading on Structural Models in Wind-Tunnel Simulated Winds", Proc. of Design Symp. on Wind Effects on High-Rise Buildings, Northwestern University, Evanston, Ill., 1970, pp. 61-88.

126. Cermak, J.E., and Chuang, H., "Vertical-Velocity Fluctuations in Thermally Stratified Shear Flows", Proc. of International Colloquium on Atmospheric Turbulence and Radio Wave Propagation, Publishing House 'Nauka' Moscow, U.S.S.R., 1965, pp. 93-104.

127. Cermak, J.E., and Nayak, S.K., "Wind-Tunnel Model Study of Downwash from Stacks of a Fossil Fuel Power Plant", Fluid Dynamics and Diffusion Laboratory, Technical Report CER72-73JEC-SKN28, Colorado State University, Fort Collins, Colorado, 1963, 77 pp.

128. Cermak, J.E., and Sadeh, W.Z., "Wind-Tunnel Simulation of Wind Loading on Structures", Meeting Paper 1417, ASCE Nat.'l Struct. Engrg. Mag., Baltimore, Md., April, 1971.

129. Chen, Y.N., "Fluctuating Lift Forces of the von Kármán Vortex Streets on Single Circular Cylinders and in Tube Bundles, Part 1-The Vortex Street Geometry of the Single Circular Cylinder, Part 2-Lift Forces of Single Cylinders, Part 3-Lift Forces in Tube Bundles", ASME Papers 71-Vibr., 11, 12, 13, 1971.

130. Chen, Y.N., "Wake Swing and Vortex Shedding in a Cross Flow past a Single Circular Cylinder", IUTAM/IAHR Symp. of Flow-Induced Structural Vibrations, Karlsruhe, Germany, August, 1972.

131. Chen. Y.N., "Frequency of the Kármán Vortex Streets in Tube Banks", J. Royal Aeronautical Society, Vol. 71, March, 1967, pp. 211-214.

132. Chen, Y.N., "Flow-Induced Vibrations in Tube Bundle Heat Exchangers with Cross and Parallel Flow, Part 1: Parallel Flow; Part 2: Cross Flow", Proc. of the Symp. on Flow Induced Vibration in Heat Exchangers, ASME Winter Annual Meeting, New York, 1970, pp . 57-74.

133. Chen, Y.N., "Fluctuating Lift Forces of the Kármán Vortex Streets on Single Circular Cylinders and in Tube Bundles, Part 1: The Vortex Street Geometry of the Single Circular Cylinder", Trans. ASME, J. Eng. for Indus., Vol. 94, 1973, pp. 603-612.

134. Chen, Y.N., "Fluctuating Lift Forces of the Kármán Vortex Streets on Single Circular Cylinders and in Tube Bundles, Part 2: Lift Forces of Single Cylinders", J. Engr. Indust., Trans. ASME, Series B, Vol. 94, No. 2, May, 1972, p. 623.

135. Chen, Y.N., "The Relationship Between the von Kármán Vortex Street and the Steady Drag of a Single Circular Cylinder", Flow-Induced Vibration in Heat Exchangers, ASME, New York, December, 1970, pp. 83-88.

136. Chen, Y.N., "the Orbital Movement and the Damping of the Fluidelastic Vibration of Tube Banks Due to Vortex Formation, Part 1: The Interplay Between the Self-Excited Vibration of the Single Circular Cylinder and the Kármán Vortex", Presented at ASME Vibrations Conference, Cincinnati, Ohio, 1973.

137. Chen,C.F., and Magione, B.J., "Vortex Shedding from Circular Cylinders in Sheared Flows", AIAA J., Vol. 7, 1969, pp. 1211-1212.

138. Chen P.W., and Robertson, L.E., "Human Perception of Thresholds on Horizontal Motion", Proc. of the Amer. Soc. of Civil Engineers, Journal of the Structural Div., Vol. 98, No. ST8, August, 1972, pp. 1681-1695.

139. Chien, N., Feng, Y., Wang, H., and Liao, T., "Wind Tunnel Studies of Pressure Distribution on Elementary Building Forms", Iowa Inst. of Hydr. Research, State Univ. of Iowa, Ames, Iowa, 1951.

140. Chiu, W.S., and Lienhard, J.H., "On Real Fluid Flow Over Yawed Circular Cylinders", J. Basic Engr., Trans. ASME, Vol. 89, 1967, pp. 815-857.

141. Chopra, K.P., and Hubert, L.F., "Mesoscale Eddies in Wake of Islands", J. Atmos. Science, Vol. 22, 1965, pp. 652-657.

142. Cincotta, J.J., Jones, G.W., and Walker, R.W., "Experimental Investigations of Wind Induced Oscillation Effects on Cylinders in Two-Dimensional Flow at High Reynolds Numbers", NASA Langley Res. Center, June, 1966.

143. Claren, R., Diana, G., Giordana, F., and Massa, E., "The Vibrations of Transmission Line Conductor Bundles", Paper 71TP 158-PWR, IEEE Winter Power Meeting, New York, N.Y., 1971.

144. Clendening, W.R., "The Effectiveness of Possible Methods for Controlling the Limit Cycle Amplitude of Galloping", Ph.D. Dissertation, Univ. Waterloo, Canada, 1972.

145. Clendening, W.R., Dubey, R.N., and Ferguson, D.C., "On the Control of Galloping System", Proc. Symp. Appl. Solid Mech., Univ. Waterloo, Canada, 1972.

146. Clendening, W.R., and Dubey, R.N., "An Analysis of Control Methods for Galloping System", ASME Paper, No. 72-WA DE-12.

147. Cohen, E., and Perrin, J., "Design of Multi-Level Guyed Towers; Wind Loading", J. Struct. Div., Proc. Amer. Soc. Civ. Eng., ST5, Paper 1255, 1957.

148. Cohen, E., and Vellozzi, J., and Suh, S.S., "Calculations of Wind Forces and Pressures on Antennas, Ann. New York Acad. Sci., Vol. 116, Art. 1, pp. 161.

149. Colin, P.E., and D'Have, R., "Execution in Tunnel Aerodynamique d'Essais sur Marquettes de Batiments en Rapport avec les Mesures Faites sur Constructions Reelles", Proc. of Conference on Buildings and Structures, National Physical Laboratory, Teddington, Great Britain, 1963, pp. 255-282.

150. Collins, G.F., "Determining Basic Wind Loads", Proc. Paper No. 825, ASCE, Vol. 81, November, 1955.

151. Conners, H.J., Jr., "Fluidelastic Vibration of Tube Arrays Excited by Cross Flow", Proc. of the Symp. on Flow-Induced Vibration in Heat Exchangers, ASME, December, 1970, pp. 42-56.

152. Cooper, K.R., "The Aeroelastic Instability of a Slender Bluff Body in a Wake Flow", Proc. 3rd Canadian Congress of Appl. Mechs., Calgary Univ., May, 1971, pp. 479-480.

153. Cooper, K.R., and Wardlaw, R.L., "Aeroelastic Instabilities in Wakes", Proc. 3rd Int. Conf. Wind Effects on Buildings and Structures, Tokyo, Vol. IV, 1971, pp. 1-1 to 1-9.

154. Counihan, J., "Lift and Drag Measurements on Stranded Cables", Imp. Coll. Aero. Dept. Rep. No. 117, 1963.

155. Cowdrey, C.F., and O'Neill, P.G., "Tests on Model Cooling Tower for C.E.A.", NPL/Aero/316a, H.M.S.O., Dec., 1956.

156. Crandall, S.H., and Mark, W.D., Random Vibration in Mechanical Systems, Academic Press, New York, 1963.

157. Cumpsty, N.A., and Whitehead, D.S., "The Excitation of Acoustic Resonances by Vortex Shedding", CUED/A-Turbo/TR 18, Cambridge University Engineering Department, 1970.

158. Curie, N., "Hydrodynamic Stability of Laminar Wakes", Phys. Fluids, Vol. 1, 1958, pp. 159.

159. Currie, I.G., Hartlen, R.T., and Martin, W.W., "The Response of Circular Cylinders to Vortex Shedding", IUTAM/IAHR Symp. on Flow-Induced Vibrations, Paper B1, Karlsruhe, Germany, August, 1972.

160. Dale, J.R., and McCandless, J.M., "Water Drag Effects of Flow Induced Cable Vibrations", ASME 68-WA/FE-47, December, 1968.

161. Dale, J.R., and Holler, R.A., "Secondary Vortex Generation in the Near Wake of Circular Cylinders", Journal of Hydronautics, Vol. 4, No. 1, January, 1970, pp. 10-15.

162. Dale, J.R., and Holler, R.A., "Vortex Wakes from Flexible Circular Cylinders at Low Reynolds Numbers", Report No. NADE-AE-7011, (MAR 645), July, 1970.

163. Dale, J.R., McCandless, J.M., and Holler, R.A., "Dynamic Response of a Suspended Hydrophone to Wave and Flow Effect", ASME 68-FE-39, (MAR 536), January, 1968.

164. Dale, J.R., Menzel, H.R., McCandless, J.H., "Dynamic Characteristics of Underwater Cables--- Flow Induced Transverse Vibrations", NAVAIRDEVCEN, Report No. NADE-AE-6620(AD-640-593), September, 1966.

165. Dale, J.R., and Menzel, H.R., "Flow Induced Oscillations of Hydrophone Cables", NAVAIRDEVCEN, 23rd Naval Underwater Sound Symp. Proc., ONR Rpt. ACR-115, Paper 3A6, December, 1965, pp. 411.

166. Dale, J.R., "Hydrodynamic Analysis of the AN/SSQ-41 Sonobuoy Hydrophone Suspension System", NAVAIRDEVCEN, Report No. NADE-AE-6636, December, 1966.

167. Davenport, A.G., "The Spectrum of Horizontal Gustiness Near the Ground in High Winds", Quart. Journal Roy. Met. Soc., Vol. 89, 1961, pp. 194.

168. Davenport, A.G., "The Applications of Statistical Concepts to the Wind Loading of Structures", Proc. Inst. of Civil Engineers, Vol. 19, 1961, pp. 449-472.

169. Davenport, A.G., "On the Statistical Prediction of Structual Performance in the Wind Environment", Paper Presented at ASCE National Structural Meeting, Baltimore,Md., Preprint 1420, 1971, 30 pp.

170. Davenport, A.G., "The Action of Wind on Suspension Bridges", Proc. Symp. on Suspension Bridges, Lisbon, Portugal, 1966, pp. 79-107.

171. Davenport, A.G., "A Rational for Determination of Design Wind Velocities", Proc. ASCE, Journal of the Structural Division, Vol. 86, 1960, pp. 39-66.

172. Davenport, A.G., "The Relationship of Wind Structure to Wind Loading", Proc. of Conf. on Buildings and Structures, National Physical Laboratory, Great Britain, Vol. 1, 1963, pp. 54-102.

173. Davenport, A.G., "Recent Developments in Statistical Treatment of Wind Loading", Proc. ASCE,EM Div., Specialty, Conf. on Probability Concepts and Methods in Eng'g., November, 1969, pp. 67-71.

174. Davenport, A.G., "Structural Safety and Reliability under Wind Action", Structural Safety and Reliability, Pergmon Press, A. Fendenthal, Ed., pp. 131-145.

175. Davenport, A.G., "The Response of Six Building Shapes to Turbulent Wind", Phil. Trans. Roy. Soc., London, A, Vol. 269, 1971, pp. 385-394.

176. Davenport, A.G., "Relationship of Wind Structure to Wind Loading", Symposium Wind Effects on Structures, Paper No. 2, H.M.S.O, 1965.

177. Davenport, A.G., "Wind Loads on Structures", Div. of Building Research Paper No. 88, Ottawa, 1960.

178. Davenport, A.G., Wind-Induced Vibration of Guyed and Self-Supporting Cylindrical Columns", Trans. E.I.C., 3,4, Dec. 1959.

179. Davenport, A.G., "Gust Loading Factors", J. Struct. Div., ASCE, Vol. 93, No. ST-3, June, 1967.

180. Davenport, A.G., and Isyunov, N., "The Application of the boundary Layer Wind Tunnel to the Prediction of Wind loading Paper 7, Proc. Int'l. Seminar on Wind Effects on Buildings and Structures, Ottawa, Canada, 11-15 Sept., 1967, Vol. 1, pp. 201-230.

181. Davenport, A.G., et al.: "A Study of Wind Action on A Suspension Bridge During Erection and on Completion", Report BLWT-3-69 Univ. of Western Ontario, London, Canada, May, 1969.

182. Davenport, A.G., "The Response of Slender, Line-Like Structures to a Gusty Wind", Paper No. 6610, Proc. Inst. of Civil Engrs., London, 1962, pp. 389-407.

183. Davey, V.S., Simpson, A., and Thomas, E.L., "A Case for Distributed Damping of Multiconductor Transmission Line Bundles", Proc. Symp. Appl. Solid Mech., Univ. Waterloo, Canada, 1972.

184. Davidson, B., Gerbier, N., Papagianakis, S.D., and Rijkoort, P.J., "Sites for Wind-Power Installations", World Methorological Organization, Tech. Note No. 63, Geneva, Switzerland, 1964, 37 pp.

185. Davis, D.A., Richards, D.J.W., and Scriven, R.A., "Investigation of Conductor Oscillation on the 275 kv Crossing over the Rivers Severn and Wye", Proc. Inst. Elect. Engineers, Vol. 110, pp. 205-220.

186. Davison, A.E., "Dancing Conductors", Trans. AIEE, Vol. 49, 1930, pp. 1444-1449.

187. Deacon, E.L., "Over-estimation of cup anemometers in fluctuating winds", J. Sci. Instr, 28.

188. Deacon, E.L., "Wind gust speed; averaging time relationship", Austral. Met. Mag., No. 52, 1965.

189. Delaney, N., and Sorensen, N.E., "Low Speed Drag of Cylinders of Various Shapes", NACA TN 3038, 1953.

190. Dickey, W.L., and Woodruff, G.B., "Vibrations of Steel Stacks", Trans. ASCE, Vol. 121, 1956.

191. Diggs, J.S., "A Survey of Vortex Shedding from Circular Cylinders with Applications Toward Towed Arrays", Naval Ship Research and Development Center Tech. Report No. 122, July, 1974.

192. Dockstader, E., "Resonant Vibration of Steel Stacks", Trans. A.S.C.E., 121, 1956, pp. 1088-1112.

193. Dockstader, E.A., Swiger, W.F., and Ireland, E., "Resonant Vibrations of Steel Stacks", Trans. ASCE, Vol. 121, 1956.

194. Docky, W. and Woodruff, G., "The Vibrations of Steel Stacks", Trans. A.S.C.E., 121, 1956, 1054-87.

195. Donaldson, C.duP., "Calculation of Turbulent Shear Flows for Atmospheric and Vortex Motions", AIAA Journal, Vol. 10, No. 1, 1972, pp. 4-12.

196. Double, E.W.W., and Tuck, W. , "Vibration of Overhead Line Conductor", Proc. IEE, Vol. 86, 1940, pp. 129-150.

197. Drescher, H., "Messund der auf Querangestromte Zylinder Ausageubten Zeitlich Beranderten Drucke", Z.f. Flugwiss, Vol. 4(½), 1956, pp. 17-21.

198. Van Driest, E.R., and Blumer, C.B., "Boundary-Layer Transition: Free-Stream Turbulence and Pressure Gradient Effects", AIAA J., Vol. 1, 1963, pp. 1303.

199. Driscoll,J.R., "Forces on Cylinders Oscillating in Water", Masters Thesis, Naval Post-Graduate School, AD-758516, December, 1972.

200. Dryden, H.L., and Hill, G.C., "Wind Pressure on Circular Cylinders and Chimneys", Research Paper No. 221, Natl. Bur. Stds., 1931.

201. Duchemin, N.V., "Recherches Experimentales Surles Lois de la Resistance des Fluides", Memorial de l'Artillerie, Vol. 5, 1842, pp. 65.

202. Dubarenko, V.V., Stepanov, D.C., and Ukhov, A.I., "Study of the Variable Random Moments of Wind Forces Acting on a Fully Steerable Antenna", A.I. Acad. Nauk SSSR, Fizicheski, Inst., Trudy 47, 1969, pp. 117-136.

203. Dugundju, J., and Mukhopadhyay, V., "Lateral Bending Torsio Vibrations of a Thin Beam under Parametric Excitation", J. of Appl. Mech., September, 1973, pp. 693-698.

204. Durand, W.F., Aerodynamic Theory, Springer, Berlin, 1934-1935.

205. Durst, C.S., "Wind Speeds Over Short Periods of Time", Met.Mag., 89, 1960, pp. 181-6.

206. Eagleson, P.S., Noutsopoulos, G.K., and Daily, J.W., "The Nature of Self-Excitation in the Flow-Induced Vibration of Flat Plates", J. of Basic Engineering, Trans., ASME, Vol. 86, 1964, pp. 599-606.

207. East, L.F., "Aerodynamically Induced Resonance in Rectangular Cavities", J. Sound Vib., Vol. 3, Part 3, 1966, pp. 277-287.

208. Edwards, A.T., and Hogg, A.D., "Wind Effects on Buildings and Structures", Proc. Int. Res. Seminar, Ottawa, Vol. 1, 1968, pp. 231-244.

209. Edwards, A.T., and Livingston, A.E., "Self-Damping Conductors for the Control of Vibration and Galloping of Transmission Line", IEEE Symp. Conductor Vib. and Galloping, Chicago, Ill., 1968.

210. Edwards, A.T., and Madeyski, A., "Progress Report on the Investigation of Galloping of Transmission Line Conductors", Trans. IEE, Vol. 75, 1956, pp. 666-683.

211. Edwards, A.T., and Hogg, A.D., "Conductor Galloping Studies at Ontario Hydro---A Progress Report", Intl. Res. Seminar on Wind Effects on Bldg. and Struc., Ottawa, Canada, 1967.

212. Edwards, A.T., "Conductor Galloping", CIGRE Study Committee, No. 22, Paper No. 22-69 (WG01) 02, 1969.

213. Edwards, A.T., Chodja, F., and Hogg, A.D., "Contact of Galloping of Overhead Conductors by the End Point Damping System", IEEE Paper No. C72 185-2, 1972.

214. Ehlers, F.E., "The Vibration of a Tight Cable Containing a Tumbuckle", Boeing Scientific Research Laboratory, Mathematical Note No. 397, March, 1965.

215. Ekman, V.W., "On Jordrotationens Inverkan pa Vind-Strommar i Hafvet", Nytt Mag. for Naturv., Vol. 40, 1902, pp. 37-63.

216. Elder, J.W., "An Experimental Investigation of Turbulent Spots and Breakdown to Turbulence", J. Fluid. Mech., Vol. 9, 1960, pp. 235.

217. Eppler, R., "Beitrage zu Theorie und Anwendung der unstetigen Stromungen", J. Rational Tech. Anal., Vol. 3, 1954, pp. 591-644.

218. van Erp. J.W.T., "Wind-Load Standards in Europe", Proc. ASCE, Vol. 76, November, 1950.

219. Etkin, B., Korbacher, G.K., and Keefe, R.T., "Acoustic Radiation from a Stationary Cylinder in a Fluid Stream (Aeolian Tones)", Journal Acoustical Society of America, Vol. 29, 1957, pp. 30-36.

220. Ezra, A.A., "Self Induced Oscillations of a Cylindrical Cantilever in a Wind for Reynolds Numbers Greater than Critical", Shock and Vibration Bulletin, Part II, U.S. Nav. Res. Lab., Washington, D.C., December, 1958.

221. Ezra, A.A., and Birnbaum, S., "Design Criteria for Space Vehicles to Resist Wind Induced Oscillations," Structure Design of Space Vehicle Conf., Santa Barbara, Calif., April, 1960.

222. Fabula, A.G., and Bedore, R.L., "Towing Basin Tests of Cable-Strumming Suppression", Naval Undersea Center, NUC TN 1188, San Diego, Calif., 1973.

223. Fage, A., "The Airflow around a Circular Cylinder in the Region where the Boundary Separates from the Surface", Phil. Mag., Fol. 7, 1929, pp. 253.

224. Fage, A., and Johansen, F.C., "On the Flow of Air Behind an Inclined Flat Plate of Infinite Span", Proc. Royal Soc., Vol. 116, No. 773, Series A, September, 1927, pp. 170-197.

225. Fage, A., and Johansen, F.C., "The Structure of Vortex Sheets", Philosophical Magazine, Vol. 25, 1957, pp. 205.

226. Fage, A., and Warsap, J.W., "The Effects of Turbulence and Surface Roughness on the Drag of Circular Cylinders", British Aeronautical Research Council, Report R & M 1283, 1929, pp. 14.

227. Fage, A., and Falkner, V.M., "The Flow around a Circular Cylinder", Aero Res. Counc., London, R & M No. 1369, 1931.

228. Faller, A.J., "An Experimental Study of the Instability of the Laminar Ekman Boundary Layer", Journal of Fluid Mechanics, Vol. 15, 1966, pp. 560-576.

229. Fanning, A.E., and Mueller, T.J., "A Numerical and Experimental Investigation of the Oscillating Flow in the Wake of Blunt Based Body", Proc. AIAA, 4th Fluid and Plasma Dynamics Conf., Paper 71-603, June, 1971, 12pp.

230. Farquharson, F.B., "The Investigation of Models of the Original Tacoma Narrow Bridge under the Action of Wind", Univ. of Washington Engrg. Experiment Sta. Bulletin, Vol. 116, Part IV, 1954.

231. Farquharson, F.B., "Aerodynamic Stability of Suspension Bridges with Special Reference to the Tocoma Narrows Bridge", University of Washington Experiment Station Engineering Bulletin, Vol. 116, Parts I-V, 1949-1954.

232. Faquharson, F.B., and McHugh,R.E.,Jr., "Wind Tunnel Investigation of Conductor Vibraiton with Use of Rigid Models", Power Apparatus and Systems, AIEE, Ocotber, 1956, pp. 871-878.

233. Farmer, M. and Jones, G.W., "Summary of Langley Wind-Tunnel Studies on Ground Wind Loads on Launch Vehicles", NASA Langley Res. Center,1966.

234. Fay, J.A., "Buoyant Plumes and Wakes", Annual Review of Fluid Mechanics, Vol. 5, 1973, pp. 151-160.

235. Feng, C.C., "The Measurement of Vortex Induced Effects in Flow Past Stationary and Oscillating Circular and D-Section Cylinders", M.A.Sc. Thesis, U. British Columbia, 1968.

236. Ferguson, N., "The Measurement of Wake and Surface Effects in the Subcritical Flow Past a Circular Cylinder at Rest and in Vortex-Excited Oscillation", Ma.A.Sc. Thesis, U. British Columbia, 1965.

237. Ferguson, N., and Parkinson, G.V., "Surface and Wake Phenomena of Vortex-Excited Oscillations of Bluff Cylinders", Trans. ASME, J. Engrg. for Indus., Vol. 89, 1967, pp. 831-838.

238. Ferguson, N., and Parkinson, G.V., "Surface and Wake Flow Phenomena of the Vortex-Excited Oscillation of a Circular Cylinder", ASME Vibrations Conference Paper, 57-Vibr. 31, Boston, 1967.

239. Ferrington, H., "Wind Loads on Buildings", Structural Engineer, Vol. 21, 1943, pp. 497.

240. Fichtl, G.H., "Longitudinal and Lateral Spectra in the Atmospheric Boundary Layer at the Kennedy Space Center", Journal of Applied Meterorology, Vol. 9, No. 1, 1970.

241. Fiedler, H., and Head, M.R., "Intermittancy Measurements in the Turbulent Boundary Layer", J. of Fluid Mech., Vol. 25-4, 1966.

242. Flachsbart, O., and Winter, H., "Modellversuche Ueber die Belastung von Gitterfachwerken Durch Wind-Kraefte", Der Stahlbau, No. 9, 10, 1934, pp. 65-73, and No. 8, 1935, pp. 65.

243. Fleming, R., Wind Stresses in Buildings, John Wiley and Sons, Inc., New York, N.Y., 1930.

244. Fluctuating Lift and Drag Acting on a Cylinder in a Flow at Supercritical Reynolds Numbers, Tech. Rep. No. GM-TR-0165-343, Space Tech. Lans., Los Angeles, 1960.

245. Forsching, H.Z., "On the Theoretical Analysis of Aeroelastically Induced Oscillations of Circular Cylindrical Structures in the Presence of Periodic Vortex Shedding", Flugwiss, Vol 18, 9/10, 1970, pp. 347-359.

246. Foss, K.A., "A Method for Computing the Mechanical Dynamic Response of Electric Power Transmission Lines", Progress Rept. No. 4, The Aeroelastic and Struct. Res. Lab., MIT, Mass., 1960.

247. Fox, N.L. and Dayman, B., Jr., Preliminary Report on Paraboloidal Reflector Antenna Wind-tunnel Tests, Report JPL, CP-3, California, 1962.

248. Frimberger, R., "Experimentelle Untersuchungen an Karmanschen Wirbelstrassen", Zeitsch f. Flugwissen., Vol. 5, 1957, pp. 355.

249. Fromm, J.E., and Harlow, F.H., "Numerical Solution of the Problem of Vortex Street Development", Physics of Fluids, Vol. 6, July, 1963, pp. 975-982.

250. Funakawa, M., "The Vibration of a Cylinder Caused by Wake Force in a Flow," JSME Bulletin, Vol. 12, Part 53, 1969, pp. 1001.

251. Fung, Y. C., An Introduction to the Theory of Aeroelasticity, John Wiley and Sons, Inc., New York, 1955.

252. Fung, Y. C., "Fluctuating Lift and Drag Acting on a Cylinder in a Flow at Supercritical Reynolds Numbers," J. Aerospace Sciences, Vol. 27, No. 11, November, 1960.

253. Gade, R. H., "Status of the Investigation of the Aerodynamic Behavior of the Sitka Harbor Bridge," Paper presented at Symposium on Full-Scale Measurements of Wind Effects on Tall Buildings and Other Structures, London, Ontario, Canada, 23-29, June, 1974.

254. Gartshore, I.S., "An Experimental Examination of the Large-Eddy Equilibrium Hypothesis", J.of Fluid Mech., Vol. 24-89, 1966.

255. Gaster, M., "Vortex Shedding from Slender Cones at Low Reynolds Numbers", J. Fluid Mech., Vol. 38, 1969, pp. 565-576.

256. Gaster, M., "Vortex Shedding from Circular Cylinders at Low Reynolds Numbers", J. Fluid Mech., Vol. 46, Part 4, pp. 749-756.

257. Gerlach, C.R., and Dodge, F.T., "An Engineering Approach to Tube Flow-Induced Vibrations", Proc. of the Symp. on Flow-Induced Vibration in Heat Exchangers, ASME Winter Annual Meeting, New York, 1970, pp. 18-26.

258. Gerlach, C.R., "Flow-Induced Vibrations of Metal Bellows", J. Engr. Ind., Trans. ASME, Vol. 91, 1969, pp. 1196-1202.

259. Gerrard, J.H., "A Disturbance-Sensitive Reynolds Number Range of the Flow Past a Circular Cylinder", J. Fluid Mech., Vol. 22, 1965, pp. 187-196.

260. Gerrard, J.H., "Three-Dimensional Structure of the Wake of a Circular Cylinder", J. Fluid Mech. Vol. 25, 1966, pp. 143-164.

261. Gerrard, J.H., "The Mechanics of the Formation Region of Vortices Behind Bluff Bodies", J. Fluid Mech., Vol. 25, 1966, pp. 401-413.

262. Gerrard,J.H., "Experimental Investigation of a Separated Boundary-Layer Undergoing Transition to Turbulence", Physics of Fluids, Vol. 10, No. 9 Part 2, 1967, pp. S98- 100.

263. Gerrard, J.H., "Numerical Computation of the Magnitude and Frequency of the Lift on a Circular Cylinder", Phil. Trans. Roy. Soc. A, Vol. 261, January, 1967, pp. 137-162.

264. Gerrard, J.H., "An Experimental Investigation of the Oscillating Lift and Drag of a Circular Cylinder Shedding Turbulent Vortices", J. Fluid Mech., Vol. 11, 1961, pp. 244-256.

265. Gerrard, J.H., "The Three-Dimensional Structure of the Wake of a Circular Cylinder", J. of Fluid Mech., Vol. 25-1, 1966.

266. Ghobarah, A.A., and Tso, W.K., "A Non-Linear Thin-Walled Beam Theory", Int. J. Mech. Sci., Pergamon Press, Vol. 13, 1971, pp. 1025-1038.

267. Gibbons, T., and Tama, M., "Measurements of the Cable Vibrations and Tension Fluctuations of the VLF Towcable", DTMB Test Report C-159-H-01, June, 1966.

268. Glass, R.J., "A Study of the Hydroelastic Vibrations of Spring Supported Cylinders in a Steady Fluid Stream due to Vortex Shedding", Ohio Northern University, Office of Naval Research Project N00014-69-C0148 Final Report, 1970.

269. Glass, R.J., "A Study of the Self-Excited Vibrations of Spring Supported Cylinders in a Steady Stream", Ph.D. Dissertation, University of Maryland, College Park, Md., 1966.

270. Glass, R.J., and Sayre, C.L.,Jr., "Amplitude and Frequency Response and Laws of Similitude for Vortex-Induced Vibrations of Spring-Supported Cylinders in Subcritical Flow", First Canadian Congress of Applied Mechanics, 1967.

271. Goldburg, A., Florsheim, B.H., and Washburn, W.K., "Strouhal Numbers for the Supersonic Wakes of Spheres and Cones", AIAA J., Vol. 3, 1965, pp. 1332-1333.

272. Goldburg, A., and Florsheim, B.H., "Transition and Strouhal Numbers for the Incompressible Wake of Various Bodies", Phys. Fluids, Vol. 9, 1966, pp. 45-50.

273. Goldman, R., "The Generation and Suppression of von Kármán Vortex Forces", Engineering Report No. 8984, Martin Co., Baltimore, Md., 1957.

274. Goldman, R.L., "Kármán Vortex Forces on Vanguard Rocket", Shock and Vibration Bulletin, Part II, Nav. Res. Lab., Washington, D.C., 1958.

275. Goldstein, S., Modern Development in Fluid Dynamics, Two Vols., Oxford University Press, London, 1938, Ch. 1 & 9, pp. 296, & Ch. 13.

276. Goldstein, S., "On the Two-Dimensional Steady Flow of a Viscous Fluid behind a Solid Body", Proc. Roy. Soc. A., Vol. 142, 1933, pp. 545.

277. Gongwer, G.A., "A Study of Vanes Singing in Water", Journal of Applied Mechanics, Vol. 19, No. 4, Trans. ASME, Vol. 74, 1952.

278. Gortler, H., "Dreidimensionale Instabilitat der Ebenen Staupenktstromung gegenuber Wirbelartigen Storungen", 50 Years of Boundary-Layer Progress, Gortler a Follmien, ed., Wieweg & Sohn, Braunschweig, 1955, pp. 304-314.

279. Gortler, H., and Witting, H., "Theorie der Sekundaren Instabilitat der Laminaren Grezschichten", Boundary Layer Research Symp., Freiburg, Springer Verlag, Berlin, 1957, pp. 110.

280. Grahm, C., "A Survey of Correlation Length Measurements, of the Vortex Shedding Process behind a Circular Cylinder", AD 650849 (MIT), October, 1966.

281. Greenspan, H.P., and Benney, D.J., "On Shear-Layer Instability Breakdown and Transition", J. Fluid Mech., Vol. 15, 1963, pp. 133.

282. Gregory, N., and Walker, W.S., "The Effect on Transition of Isolated Surface Excrescences in the Boundary Layer", Aero. Res. Comm., London, Res. and Memo. No. 2779, 1956.

283. Griffin, O.M., "Flow Near Self-Excited and Forced Vibrating Circular Cylinders", Trans., ASME, Journal of Engineering for Industry, Vol. 94, May, 1972, pp. 539-554.

284. Griffin, O.M., "The Unsteady Wake of an Oscillating Cylinder at Low Reynolds Number", NRL, Journal of Applied Mechanics, December, 1971, pp. 729-738.

285. Griffin, O.M., and Skop, R.A., "A Model for the Vortex-Excited Resonant Response of Bluff Cylinders", NRL, Journal of Sound and Vibration, Vol. 27, 1973, pp. 225-233.

286. Griffin, O.M., Skop, R.A., Koopman, G.H., "The Vortex Excited Resonant Vibrations of Circular Cylinders", J. Sound and Vibrations, 31, 2, 1973.

287. Griffin, O.M., Skop, R.A., and Koopman, G.R., "Measurements of the Response of Bluff Cylinders to Flow-Induced Vortex Shedding", Offshore Technology Conference Paper, OTC 1814, May, 1973.

288. Griffin, O.M., and Skop, R.A., "An Heuristic Model for Determining Flow-Induced Vibrations of Offshore Structures", Offshore Technology Conference Paper, OTC 1814, May, 1973.

289. Griffin, O.M., "The Effects of Synchronized Cylinder Vibration on Vortex Formation and Strength, Velocity Fluctuations, and Mean Flow", NRL, Symposium on Flow-Induced Structural Vibrations, Paper E3, Karlsruhe, Germany, August, 1972.

290. Griffin, O.M., and Votaw, C.W., "The Use of Aerosols for the visualization of Flow Phenomena", NRL. Int. Journal of Mass Transfer, Vol. 16, July, 1972, pp. 217-219.

291. Griffin, O.M., and Ramberg, S.E., "On Vortex Strength and Drag in Bluff Body Wakes", J. Fluid Mech., 1975.

292. Griffin, O.M., and Ramberg, S.E., "The Vortex-Street Wakes of Vibrating Cylinders", J. Fluid Mech., Vol. 66, 1974, pp. 553-578.

293. Griffin, O.M., Skop, R.A., and Koopman, G.H., "The Vortex Excited Resonant Vibration of Circular Cylinders", J. Sound Vib., Vol. 31, 1973, pp. 235-249.

294. Griffin, O.M., and Votaw, C., "The Vortex Street in the Wake of a Vibrating Cylinder", Journal of Fluid Mechanics, Vol. 55, 1972, pp. 31-48.

295. Griffin, O.M., Skop, R.A., and Ramberg, S.E., "The Resonant, Vortex-Excited Vibrations of Structures and Cable Systems", Offshore Technology Conference, Paper No. OTC 2319, 1975.

296. Grotz, B.J., and Arnold, F.R., Flow Induced Vibrations in Heat Exchangers, Stanford University, Dept. of Mech. Eng., Tech. Report 31, 1956.

297. Halle, H., "Proposed Analytical Model for the Cross-Flow-Induced Vibrations of a Circular Cylinder", Proc. Conf. Flow-Induced Vibrations in Reactor System Components, Argonne Lab., May, 1970, pp. 248-269.

298. Hama, F., "Three-Dimensional Vortex Pattern Behind a Circular Cylinder", Journal of the Aeronautical Sciences, Vol. 24, 1957, pp. 156-158.

299. Hama, F.R., "Progressive Deformation of a Curved Vortex Filament by Its Own Induction", Physics of Fluids, Vol. 5, 1962, pp. 1156.

300. Hama, F.R., "Some Transition Patterns in Axisymmetric Boundary Layers", Physics of Fluids, Vol. 2, 1959, pp. 664.

301. Hama, F.R., "Streaklines in a Perturbed Shear Flow," Physics of Fluids, Vol. 5, 1962, pp. 644.

302. Hama, F.R., "Progressive Deformation of a Perturbed Line Vortex Filament," Physics of Fluids, Vol. 6, 1963, pp. 526.

303. Hama, F. R., "Boundary-Layer Transition Induced by a Vibrating Ribbon on a Flat Plate," Proc. Heat Transfer and Fluid Mech., Stanford Univ. Press, 1960, pp. 92.

304. Hama, F.R., and Nutant, J., "Detailed Flow-Field Observations in the Transition Process in a Thick Boundary Layer," Proc. Heat Transfer and Fluid Mech., Stanford Univ. Press, 1963.

305. Hama, F.R., and Nutant, J., "Self-Induced Velocity on a Curved Vortex," Physics of Fluids, Vol. 4, 1961, pp. 28.

306. Hamilton,G.F., Effect of Velocity Distribution on Wind Loads on Walls and Low Buildings, University of Toronto, TP 6205, Nov. 1962.

307. Hanna, S.R., "Characteristics of Winds and Turbulence in the Planetary Boundary Layer", ESSA Research Laboratories, Air Resources Laboratory, Oak Ridge, Tennessee, Technical Memorandum ERLTM-ARL 8, 1969, 61pp.

308. Hansen, M., "Velocity Distribution in the Boundary Layer of a Submerged Plate", NACA Tech. Memo., 585, 1930.

309. Hanson, A.R., "Piezoelectric Gauge for Measuring Cylinder Drag in a Fluctuating Airstream", Rev. Sci. Instr., Vol. 36, 1965, pp. 359-363.

310. Hanson, A.R., "Vortex Shedding from Yawed Cylinders", AIAA J., Vol. 4, 1966, pp. 738-740.

311. Hanson, P.N., and Jones, G.W., "On the Use of Dynamic Models for Studying Launch Vehicle Buffet and Ground Wind Loads", Proc. Symp. Aero and Dyn. Modeling Tech., RTD-TDR-63-4197, 1963, pp. 334-387.

312. Hanson, R.B., and Richardson, P.D., "Hot Wire Measurements in the Near Wake of a Circular Cylinder", Brown University Dept. w742, 1965.

313. Hanson, A.R., and Richardson, D.D., "The Near-Wake of a Circular Cylinder in Crossflow", Trans. ASME, J. of Basic Engineering, December, 1968, pp. 476-484.

314. Hardwick, J.D., and Wootton, L.R., "The Use of Medel and Full-Scale Investigations on Marine Structures", Proc. International Symp. on Vibration Problems in Industry, Paper No. 127, 16pp.

315. Harlow, H.F., and Fromm, E.J., "Dynamics and Heat Transfer in the von Kármán Wake of a Rectangular Cylinder", The Physics of Fluids, Vol. 7, No. 8, August, 1964.

316. Harris, C.P., "Galloping Conductors", Dept. Engr. Mech., Univ. of Notre Dame, South Bend, Ind. 1949.

317. Harris, R.I., On the Spectrum and Auto-correlation Function of Gustiness in High Winds, E.R.A. report SP1/T14.

318. Harris, R.I., "The Nature of the Wind", Paper No. 3 in The Modern Design of Wind-Sensitive Structures, Proc. of Seminar June 1970 in London. Published by Construction Industry Research and Information Ass'n, London, 1971, pp. 29-55.

319. Hartlen, R.T., and Currie, I.G., "Lift-Oscillation Model for Vortex-Induced Vibration", Proceedings of American Society of Civil Engineers, Journal of Engineering Mechanics, Vol. 96, 1970, pp. 577-591.

320. Hartlen, R.T., Baines, W.D., and Currie, I.G., "Vortex-Excited Oscillations of a Circular Cylinder", University of Toronto Technical Report 6809, 1968.

321. den Hartog, J.P., Mechanical Vibrations, 4th Ed., McGraw-Hill, New York, 1960, Sec. 62, 63.

322. den Hartog, J.P., "Transmission Line Vibration due to Sleet", Trans. AIEE, Vol. 49, 1930, pp. 444.

323. den Hartog, "Recent Technical Manifestations of von Kármán's Vortex Wake", Proc. Natl. Academy of Sci., Vol. 40, No. 3, 1954, pp. 155-157.

324. Heisenberg, W., "Die absoluten Dimensionen der Karmanschen Wirbelbewegung", Phys. Z., Vol. 23, 1922, pp. 363.

325. Herrmann, G., and Hauger, W., "On the Interrelation of Divergence, Flutter and Auto-Parametric Resonance", Ingenieur-Archiv., Vol. 42, 1973, pp. 81-88.

326. Heskestad, G. , and Olberts, D.R., "Influence of of Trailing-Edge Geometry on Hydraulic-Turbine-Blade Vibration Resulting From Vortex Excitation", J. of Engineering for Power, Trans. ASME, Vol. 82, 1960, pp. 103-110.

327. Hide, R., and Ibbetson, A., "An Experimental Study of 'Taylor Columns'", Icarus, Vol. 5, 1966, pp. 279.

328. Hill, R.S., and Armstrong, C., "Aerodynamic Sound in Tube Banks", Proc. Phys. Soc., 79, 1, 1962, pp. 225.

329. Hill, R.S., and Pennington, B., "The Direct Measurement of Fluctuating Aerodynamic Forces Experienced by an Effectively Stationary Body Spanning a Wind Tunnel", Proc. Int. Congr. on Instrumentation in Aerospace Simulation Facilities, June, 1971, pp. 111-118.

330. Hino, M., and Kaneko, D., "Interaction between an Oscillating Plate and Shedding Vortices", Proc. 3rd International Conference on Wind Effects on Buildings and Structures", Tokyo, IV, 31, September, 1971, 9pp.

331. Hirai, A., Okachi, I., Ito, M., and Miyata, J.: "Studies on the Critical Wind Velocity for Suspension Bridges", Paper 30, Int'l Seminar on Wind Effects on Buildings and Structures, Ottawa, Canada, Vol. 11, 11-15, September, 1967, pp. 81-103.

332. Hirai, A., Okauchi, I., and Miyata, J., "On the Behaviour of Suspension Bridges under Wind Action", Proc. Symp. on Suspension Bridges, Lisbon, Portugal, 1966.

333. Hirsch, G., and Ruscheweyh, H.: "Full-Scale Measurements on Steel Chimney Stacks", Paper presented at Symposium on Full-Scale Measurements of Wind Effects on Tall Buildings and Other Structures, London, Ont., Canada, 24-28 June, 1974.

334. Hoecker, W.H., Jr., "Three-Dimensional Pressure Pattern of the Dallas Tornado and Some Resultant Implications", Monthly Weather Review, Vol. 89, No. 12, 1961, pp. 533-542.

335. Hoeltzel, G., "Ein Beitrag zum Problem winderregter Querschwingungen kreiszylindrischer Staebe im unterkritischen Reynolds bereich", Dissertation TU Dresden, Fakultaet fuer Bauwessen, Dresden, 1968, 115pp.

336. Hoerner, S.F., Fluid Dynamics Drag, Published by the author, Midland Park, New Jersey, 1965.

337. Hogg, A.D., and Edwards, A.T., "The Status of Conductor Galloping Problem in Canada", Seminar on Wind Effects on Bldg. and Struct., Teddington, England, Paper No. 12, Ref. 1, 1963.

338. Hogg, A.D., and Edwards, A.T., "Conductor Galloping Studies in Ontario Hydro", Paper No. 8, Ref. 3, 1967.

339. Hollingdale, S.H., "Stability and Configuration of the Wakes Produced by Solid Bodies Moving through Fluids", Phil. Mag. Ser. 7, Vol. 29, 1940, pp. 211.

340. Homann, F., "Einfluss grosser Zeehigkeit bei Stroemung um Zylinder un Kugel", Forsch. Ing. Wes., Vol. 7, 1936, pp. 1-10.

341. Honji, H., and Taneda, S., "Vortex Wakes of Oscillating Circular Cylinders", Reports of Research Institute for Applied Mechanics, Kyushu University, Vol. 16, 1968, pp. 211-222.

342. Hooker, S.G., "On the Action of Viscosity in Increasing the Spacing Ratio of a Vortex Street", Proc. of the Royal Society, Series a., Vol. 154, 1936, pp. 67-89.

343. Hoot, T.G., and Meroney, R.N., "The Behavior of Negatively Buoyant Stack Gases", Preprint Paper No. 74-120, 67th Annual Meeting of the Air Pollution Control Association, Denver, Colo., June, 1974, 20pp.

344. Hore, P.S., "Vibration of a Suspended Elastic Cable", S.M. Thesis, MIT, Aero. and Astro. Dept., June, 1970.

345. Horne, M.R., "Wind Loads on Structures", J. Inst. Civ. Engrs., Vol. 33, January, 1950, pp. 155.

346. Hoult, D.P., and Weil, J.C., "Turbulent Plume in a Laminar Cross Flow", Atmospheric Environment, Vol. 6, 1972, pp. 513-531.

347. Hoven, I. van der, "Power Spectrum of Horizontal Wind Speed in the Frequency range from 0-0007 to 900 Cycles/hour", J. Met. 14, 160, 1957.

348. Howard, L.N., and Matthews, D.L., "On Vortices Produced in Shock Diffraction", J. Applied Physics, Vol. 27, 1956, pp. 223.

349. Howe, J.W., "Wind Pressure on Elementary Building Fomrs Evaluated by Model Tests", Civil Engineering, pp. 42, May, 1952.

350. Hoyer, W., and Hoeltzel, G., "Untersuchungen ueber den Erregungscharakter winderregter Querschwinguengn Kreiszylindrischer Staebe im unterkritischen Renolds-Bereich", Int. Assoc. Bridge Structural En., 8th Congr., New York, Sept. 9-14, Reprint from the final report, published by the Secretariat of JASSE, Zuerich, pp. 1157-1168.

351. Hsu, C.T., "Laboratory Modeling of the Tornado Suction Mechanism", Preprints of Eighth American Meteriological Society Conference on Severe Local Storms, Denver, Colorado, October, 1973, pp. 199-202.

352. Hsu. E.Y., and Macovsky, M.S., "Measurement of Transition on a Sphere at High Reynolds Numbers", David Tylor Model Basin, Rept. 1110, 1957.

353. Hubert, L.F., and Krueger, A.F., "Satellite Pictures of Mesoscale Eddies", Monthly Weather Rev. Vol. 90, 1962, pp. 457-463.

354. Huh, C.K., "The Behaviour of Lift Fluctuations on the Square Cylinders in the Wind Tunnel Test", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, IV, September, 1971, 10pp.

355. Hull, F.H., "Stability Analysis of Multi-Level Guyed Towers", J. Struct. Div., Proc. Amer. Soc. Civ. Eng., Paper 1391, 1962.

356. Humphreys, J.S., "On a Circular Cylinder in a Steady Wind at Transition Reynolds Numbers", Journal of Fluid Mechanics, Vol. 9, 1960, pp. 603-612.

357. Humphreys, J.S., "On a Circular Cylinder in a Steady Wind', Ph.D. Thesis, Harvard University, 1959.

358, Hunt, J.C.R., "A Theory of Turbulent Flow Around Two-Dimensional Bluff Bodies", Journal of Fluid Mechanics, Vol. 61, Part 2, 1973, pp. 245-274.

359. Hunt, J.C.R., and Mulhern, P.J., "Turbulent Dispersion from Sources Near Two-Dimensional Obstacles", Journal of Fluid Mechanics, Vol. 61, Part 2, 1973, pp. 245-274.

360. Hunt, J.C.R., and Richards, D.J.W., "Overhead Line Oscillations and the Effect of Aerodynamic Dampers", Proc. IEE, Vol. 116, 1969, pp. 1869-1874.

361. Imai, I., "Theory of Bluff Bodies," Univ. Maryland Inst. Fluid Dyn. and Applied Math., Tech. Note, No. BN-104, June, 1957.

362. Irminger, I., "Experiments on Wind Pressure," Proc. Inst. of Civil Engrs., Vol. 118, 1893-1894, pp. 468-472.

363. Ishizake, H., "Effects of Wind Pressure Fluctuation on Structures, International Research Seminar", Wind Effects on Buildings and Structures, N.R.C., Ottawa, 1967.

364. Isyumon, N., Abu-Sitta, S.H., and Davenport, A.G., "Approaches to the Design of Hyperbolic Cooling Towers Against the Dynamic Action of Wind and Earthquake", Int. Asso. Shell Struct. Bull., Vol. 48, 1972, pp. 3-22.

365. Isyumov, N., Jandali, T., and Davenport, A.G., "Model Studies and the Prediction of Full Scale Levels of Stack Gas Concentrations", Preprint paper No. 74-162, 67th Annual Meeting of the Air Pollution Control Association, Denver, Colo., June,1974, 33pp.

366. Iverson, J.D., Greeley, R.,Pollack, J.,B., and White, B.R., "Simulation of Martian Eolian Phenomena in the Atmospheric Wind Tunnel", Engineering Research Institute, Technical Paper ERI-73083, Iowa State University, Ames,, Iowa, 1973, 25pp.

369. Iwan, W.D., and Blevins, R.D., "A Model for Vortex Induced Oscillation of Structures", Trans. ASME , J. Appl. Mech., Vol. 41, 1974, pp. 581-586.

368. Jaminet, J.F., and van Atta, C.W., "Experiments on Vortex-Shedding from Rotating Circular Cylinders", AIAA J., Vol. 7, 1969, pp. 1317-1319.

369. Jensen, M., "The Model-Law for Phenomena in Natural Wind", Ingeniøren, Vol. 2, No. 4, 1958, pp. 121-128.

370. Jenson, M. and Franck, N., Model Tests in Turbulent Wind, Part 1, Danish Technical Press, Copenhagen, 1963.

371. Johns, D.J., "Wind-Excited Behaviour of Cylindrical Structures; Its Relevance to Aerospace Design", AGARD CP No. 48, Paper No. 25, 1969.

372. Johns, D.J., "Aerospace Technology - Its Challenge and Spinoff: Some Aeroelastic Problem in Aeronautical and Civil Engineering", British Assoc. for Adv. of Sci. Annual Meeting, Section G, Paper 15T, September, 1970, 22pp.

373. Johns, D.J., and Allwood, R.J., "Wind-Induced Ovalling Oscillations of Circular Cylindrical Shell Structures", Paper 28, Loughborough Conference, 1968.

374. Jones, G.W., Jr., "Unsteady Lift Forces Generated by Vortex Shedding about a Large Stationary, and Oscillating Cylinder at High Reynolds Numbers", Symp. on Unsteady Flow, ASME Paper No. 68-FE-36, 1968.

375. Jones, F.W.,Jr., Cincotta, J.J., and Walker, R.W., "Aerodynamic Forces on a Stationary and Oscillating Circular Cylinder at High Reynolds Numbers", NASA Tech. Rep. TR R-300, 1969, 62pp.

376. Jordan, S.K., and Fromm, J.E., "Oscillatory Drag, Lift, and Torque on a Circular Cylinder in a Uniform Flow", Phys. Fluids, Vol. 15, No. 3, March, 1972, pp. 371-376.

377. Kaimel, J.C., "Turbulence Spectra, Length Scales and Structure Parameters in the Stable Surface Layer", Boundary-Layer Meteorology, Vol. 4, April, 1973, pp. 289-309.

378. Kaimal, J.C., Wyngaard, J.C., Izumi, T., and Cote, O.R., "Spectral Characteristies of Surface-Layer Turbulence", Quarterly Journal of the Royal Meteorological Society, Vol. 98, 1972, pp. 563-589.

379. Kaplun, S., "Low Reynolds Number Flow Past a Circular Cylinder", J. Math. & Mech., Vol. 6, 1957, pp. 237.

380. von Kármán, T., and Rubach, H., "Uber den Mechanismus des Flusigkeits und Luftwiderstandes", Phys. Zeits., Vol. 13, 1912.

381. von Kármán, T., "Mechanische Ahnlichkeit und Turbulenz", Nachr. Ges. Wiss, Gottingen, Math-Phys. Kl, 1930, pp. 58-76.

382. von Kármán, T., "Aerodynamics and the Art of the Engineer", Memoires de la Societe des Ingenieurs Civils de France, 1948, pp. 155-178.

383. von Kármán, T., "Uber den echanismus de Widerstands, den ein bewegter Korper in einer Flussigkeit erfahrt", Gottinger Nachrichten, Math. Phys. Kl., 1911, pp. 509-519.

384. von Karman, T., and Dunn, L.G., "Wind Tunnel Investigations at Cal. Inst. of Tech.", Ch. VII of Aerodynamic Stability of Suspension Bridges, Engr. Exp. Sta. Bulletin 116, Part II, Editor: F.B. Farquharson, Univ. of Washington, June 1952.

385. von Karman, T., and Dunn, L.G., Contribution to Aerodynamic Stability of Suspension Bridges, Parts 1-5, Farquharson, F.B., Ed., Structural Research Laboratory, Univ. of Washington, 1949-1954.

386. Karnopp, B.H., and Fung, J.C., "On the Approximate Determination of Natural Frequencies and Modes of Cantilevered Beams", Acta Mechanica, Vol. 9, Part 1-2, pp. 109-120.

387. Katzmayr, R., "Wind Pressure on Engineering Structures", Oesterr, Ing., Arch. Verein, Vienna, Vol. 82, No. 21-22, 1930, pp. 175, and No. 23-24, pp. 191.

388. Katzmayr, R., and Seitz, H., "Winddruck auf Fachwektuerme von quadratischem Querschnitt", Bauingenieur, Vol. 15, 1934, pp. 215-221.

389. Kawaguti, M., "Numerical Solution of the Navier-Stokes Equations for the Flow around a Circular Cylinder at Reynolds Numbers 40 and 44", Rept. to Aero. Res. Council No. 20502, London, 1958.

390. Kawamura,S., "A Design Criterion of Wind Loads of High Steel Stacks", Proc. 3rd Int. Conf. Wind Effects on Building and Structures, Tokyo, 1971, pp. 707-716.

391. Keefe, R.T., "An Investigation of the Fluctuating Forces Acting on a Stationary Circular Cylinder in a Subsonic Stream and of the Associated Sound Field", Institute of Aerophysics, University of Toronto, Report No. 76, September, 1961.

392. Kelly, R.E., and Guff, C.N., "Drag and Vibrations of some Wire Ropes and Fairings", U.S. Mine Defense Lab. Report i-132, September, 1967.

393. Kessler, E., "Survey of Boundary Layer Winds with Special Reference to Extreme Values", Paper 74-586, 7th Plasma and Fluid Dynamics Conference, American Institute of Aeronautics and Astronautics, Palo Alto, California, June, 1974, 19pp.

394. Keulegan, G.H., and Carpenter, L.H., "Forces on Cylinders and Plates in an Oscillating Fluid", J. Res. Nat. Bur. Standards, Vol. 60, 1958, pp. 423-440.

395. Kimura, H., "Estimation of Oscillatory Aerodynamic Forces in Separated Flow", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, IV, 33, September, 1971, 10pp.

396. King, R., "The 'Added Mass' of Cylinders", The British Hydromechanics Research Association, Report No. TN1100, April, 1971.

397. King, R., and Prosser, M.J., "On Vortex Excitation of Model Piles in Water", Journal of Sound and Vibration, Vol. 29, Part 2, 1973, pp. 169-188.

398. King, R., "Flow Induced Vibrations", The British Hydromechanics Research Association Report RR 1093, January, 1971.

399. King, R., "Vortex-Excited Structural Oscillations of a Circular Cylinder in Steady Currents", Offshore Technology Conference Pre-print, 1974.

400. King, R., and Prosser, M.J., "Criteria for Flow-Induced Oscillations of Cantilevered Cylinders in Water", Proc. of the Symp. on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper E5, 1972.

401. King, R., "The Hydrodynamic Damping of Natural Vibrations of a Cantilevered Cylinder in Water", The British Hydromechanics Research Association, Report RR11 2, 1972.

402. Klebanoff, P.S., Schubauer, G.B., and Tidstrom, K.D., "Measurements of the Effect of Two-Dimensional and Three-Dimensional Roughness Elements on Boundary Layer Transition", J. Aero. Sci., Vol. 22, 1955, pp. 803.

403. Klebanoff, P.S., and Tidstrom, D.D., "Evolution of Amplified Waves Leading to Transition in a Boundary Layer with Zero Pressure Gradient", NASA Tech. Note D-195, 1959.

404. Kebanoff, P.S., Tidstrom, K.D., and Sargent, L.M., "The Three-Dimensional Nature of Boundary-Layer Instablility", J. Fluid Mech., Vol. 12, 1962, pp. 1.

405. Klemin, A., Schaefer, E.B., and Burer, L.H., Jr., "Aerodynamics of the Perisphere and Trylon at the World's Fair", Trans. ASCE, Vol. 104, 1939, pp. 1449.

406. Knonauer, R.E., "Predicting Eddy Frequency in in Separated Wakes", IUTAM Symposium, Univ. of Michigan, July, 1964.

407. Kobashi, Y., and Onzi, A., "Stability of a Boundary Layer with Time-Dependent Outside Flow", Nat. Aero. Lab. Rept. Tokyo, 1962.

408. Koopmann, G.H., "The Vortex Wakes of Vibrating Cylinders at Low Reynolds Numbers", J. Fluid Mech., Vol. 28, 1967, pp. 501-512.

409. Koopmann, G.H., "Wind Induced Vibrations of Skewed Circular Cylinders", MS Thesis, The Catholic University of America, Washington, D.C., 1967.

410. Kortschinske, J., "Line Ice Detectors for the Indication and Study of Conductor Galloping", IEEE Winter Power Mtg. Conf., Paper No. 68-CP67-PWR, 1968.

411. von Koten, H., Some Measurements on Tall Buildings in the Netherlands, Inst. T.N.O., B.B.C., Tower Block, NPL. Aero/1032, 1964.

412. von Koten, H., "A Lighting Tower as an Example of a Simple Structure Loaded by Wind", De Ingenieur, Vol. 84, July, 1972, pp. B67 - B 75.

413. Kovasznay, L.S.G., "Hot-Wire Investigation of the Wake Behind Cylinders at Low Reynolds Numbers", Prc. Roy. Soc. London, Ser. A, Vol. 198, 1949, pp. 174-190.

414. Kovaszvay, L.S.G., Komoda, H., and Vasudeva, B.R., "Detailed Flow Field in Transition", Proc. Heat Transfer and Fluid Mech., Stanford Univ. Press, 1962.

415. Kraemer, K., "Uber die Wirkung von Stolpeldrahten auf den Grenzschitumbschlag", Zeit.Flugwissen, Vol. 9, 1961, pp. 20.

416. Kramer, C., "Stroemungsuntersuchungen an Zylindergittern", Dissertation, TH Aachen, 1966, 119pp.

417. Kronauer, R.E., "Predicting Eddy Frequency in Separated Wakes", IUTAM Symp. Concentrated Vortex Motions in Fluids, Ann Arbor, Michigan, 1964.

418. Kronauer, R.E., and Abernathy, F.H., "The Formation of Vortex-Street", Journal of Fluid Mech., Vol. 13, Part 1, May, 1962, pp. 1-20.

419. Krzywoblocki, M.Z., "Investigation of the Wing-Wake Frequency with Application of the Strouhal Number", Journal of Aerospace Science, Vol. 12, No. 1, 1945, pp. 51.

420. Kuo, H.L.,"On the Dynamics of Convective Atmospheric Vortices", Journal of the Atmospheric Sciences, Vol. 23, 1966, pp. 25-42.

421. Kuo, H.L., "Note on the Similarity Solution of the Vortex Equations in an Unstable Atmosphere", Journal of the Atmospheric Sciences, Vol. 24, 1967, pp. 95-97.

422. Kuo, H.L., "Axisymmetric Flows in the Boundary Layer of a Maintained Vortex", Journal of the Atmospheric Sciences, Vol. 28, No. 1, January, 1971, pp. 20-41.

423. Laird, A.D.K., "Eddy Formation Behind Circular Cylinders", J. Hydraulic Division, Proc. ASCE, 763, June, 1971.

424. Lamb, H., Hydrodynamics, 6th Ed., Dover, New York, 1946.

425. Lambert, P., and Leon, P., "Experimental Determination of Fluctuating Hydrodynamical Forces in the Tanks of the Phenix Reactor", La Houille Blanche, No. 6, 1971, pp. 499-503.

426. Landl, R., "Lift Forces on an Oscillating Cylinder at Low Reynolds Numbers", IUTAM Symp. Unsteady Boundary Layers, Laval Univ., Quebec, Canada, Vol. 24-28, May, 1971.

427 Landweber, L., and Grimminger, G., "Progress Report on the Lateral Vibration of Circular Cylinders Caused by Motion Through a Fluid", DTMN Technical Note.

428. Laneville, A., and Parkinson, G.V., "Effects of Turbulence on Galloping of Bluff Cylinders", Proc. 3rd Int. Conf. Wind Effects on Buildings and Structures, Tokyo, 1971, IV.

429. Lavery, T.F., Egan, B.A., and Iwanchuk, R.M., "The Numerical Simulation of the Advection and Diffusion of a Plume Under Aerodynamic Downwash Conditions", Reprint Paper No. 74-215, 67th Annual Meeting of the Air Pollution Control Association, Denver, Colo., June, 1974, 16pp.

430. Lazan, B.J., Damping of Materials and Members in Structural Mechanics, Pergamon Press., New York, 1968.

431. Lecher, W.A., "Consideration of Similarity for Hydroelastic Vibrations", Proc. Inst. Mech. Engrs., Vol. 18, No. 25, 1967.

432. Lehnert, R., "Akystische Messugnen an Wirbelstrassen Hinter Kreiszylinder und Ebener Platte", Phys. Zeit., Vol. 38, 1937, pp. 476.

433. Leutheusser, H.J., and Motycka, J., "Redesign of Refinery Stacks by Wind Tunnel Tests to Meet Changes in Crude Oil Quality", Preprent Paper No. 74-163, 67th Annual Meeting of the Air Pollution Control Association, Denver, Colo., June, 1974, 21pp.

434. Liepmann, H.W., "Free Turbulent Flows", Publ. Centre National de la Recherche Scientifique, Paris, 1962, pp. 211.

435. Lin, C.C., "On Periodically Oscillating Wakes in the Oseen Approximation", Studies in Mathematics and Mechanics, New York, Academic, 1954, pp. 170-176.

436. Lin, C.C., The Theory of Hydrodynamic Stability, Cambridge University Press, 1955.

437. Livesey, J.L. and Dye, R.C.F., "Vortex Excited Vibration of a Heat Exchanger Tube Row", J. of Mechanical Eng. Sci., 4, 4, 1962.

438. Lochtenberg, B.H., "Transition in a Separated Laminar Boundary Layer", J. Aerospace Science, Vol. 27, 1960, pp. 92.

439. Loiseau, H., and Szechenyi, E., "Etude du Comportement Aéroélastique du Tablier d'un Pont à Haubans, T.P. 1975, ONERA, 92320 Châtillon, France.

440. Lord, G.R., and Leutheusser, H.J., "Wind-Tunnel Modeling of Stack Gass Discharge", Man and His Environment, Vol. 1, Pergamon Press, Inc., 1970, pp. 115-125.

441. Lundgren, T.S., "Turbulent Pipe and Channel Flow", Physics of Fluids, Vol. 14, No. 2, 1971, pp. 225-230.

442. Lyon, R.H., "The Transmission of Vibrations by Towed Cables", Bolt, Beranek and Newman, Report No. 934, Job No. 11072, Contract Nonr 3468(00) Task NR, May, 1962, pp. 385-424.

443. Macovsky, M.S., "Vortex Induced Vibration Studies", David Taylor Model Basin Report 1190, 1958.

444, Madderom, P., "Two-Vortex Potential Model for Turbulent Flow past Circular Cylinders", UBCME Dept. Unpublished Note, April, 1966.

445. Maekawa, T., and Mizuno, S., "Flow around the Separation Point and in the Near-Wake of Circular Cylinder", Physics of Fluids, Vol. 10, No. 9, Part 2, 1957.

446. Maher, F.J., Frederick, D., Estes, E.R., and Steinman, D.B., "Wind Tunnel Tests of Suspension Bridge Section Models", Bulletin, Va. Polytech. Inst. Engrg. Experiment Sta., Vol. 41, No. 6, Series No. 69, 1948.

447. Maidanik, G., "Energy Dissipation Associated with Gas-Pumping in Structural Joints", Journal of the Acoustical Society of America, Vol. 40, No. 5, 1966, pp. 1064-1072.

448. Mair, W.A., and Maull, D.J., "Bluff Bodies and Vortex Shedding---A Report on Euromech 17", Journal of Fluid Mechanics, Vol. 45, Part 2, 1971, pp. 209-224.

449. Mair, W.A., and Maull, D.J., "Aerodynamic Behavior of Bodies in the Wake of Other Bodies", Phil. Trans. Roy. Soc., London A, Vol. 269, 1971, pp. 425-437.

450. Majumdar, A.S., and Douglas, W.J.M., "Autocorrelation Measurements in the Nearwake of Square Section Cylinder in Turbulent Free Stream", Physics of Fluids, June, 1970.

451. Manuzio, C., "Wind Effects on Suspended Cables", International Reasearch Seminar on Wind Effects on Buildings, Ottawa. 1967.

452. Marchman, J.F., "Wind Effects on Floating Surface in Large Open Top Storage Tanks", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, II, 15, September, 1971, 8pp.

453. Marris, A.W., "A Review of Vortex Streets, Periodic Wakes, and Induced Vibration Phenomena", Trans. ASME, J. Basic Eng., Vol. 86, 1964, pp. 185-196.

454. Marris, A.W., "The Generation of Secondary Vorticity is an Incompressible Fluid", Journal of Applied Mechanics, Trans. ASME, Vol. 85, Series E, 1963, pp. 525-531.

455. Marris, A.W., and Brown, O.G., "Hydrodynamically Excited Vibrations of Cantilever-Supported Problems", ASME Paper, No. 62-Hyd-7.

456. Marshall, R.D., and Cermak, J.E., "Wind Studies of Bank of American World Headquarters Building---Part II, Wind Tunnel Study", Fluid Dynamics and Diffusion Laboratory, Technical Report, CER66-67RDM-JE19, Colorado State University, Fort Collins, Colo., 1966, 66pp.

457. Makell, E.C., "A Theory of Blackage Effects on Bluff Bodies and Stalled Wings in a Closed Wind Tunnel", Paper No. Aero 2685, Royal Aircraft Estab., Farnborough. Hants, (England).

458. Matsumoto, M., "The Dynamical Forces Acting on the Vibrating Square Prism in a Steady Flow", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, IV, 27, September, 1971, 10pp.

459. Mattingly, G.E., "An Experimental Study of the Three-Dimensionality of the Flow around a Circular Cylinder", Inst. for Fluid Dyn. and Appl. Math., Univ. of Maryland, Tech. Note BN-295, 1962.

460. Maull, D.J., "The Wake Characteristics of a Bluff Body in a Shear Flow", Paper 16, AGARD Conference Proceedings, No. 48, 1969.

461. Maull, D.J., and Young, R.A., "Vortex Shedding from a Bluff Body in a Shear Flow", IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, No. H2, August, 1972.

462. Maybrey, J.F.M., "Wind Tunnel Investigation of the Instability of an All-Welded Vehicle/Pedestrian Parapet", NPL Tech. Memo. Mar. Sci. TM 101, December, 1972, 17 pp.

463. Mei, V.C., and Currie, I.G., "Flow Separation on a Vibrating Circular Cylinder", Physics of Fluids, Vol. 12, No. 11, 1969, pp. 2248-2254.

464. Meier-Windhorst, "Flow Induced Vibrations of Cylinders in Uniform Flow", Munich Technische Hochschule, Hydraulische Inst., Mitt Heft 9 (David Taylor Model Basin Translation 333), August, 1939.

465. Melbourne, W.H., and Joubert, P.N., "Problems of Wind Flow at the Base of Tall Buildings", Proc. of 3rd International Conf. on Wind Effects on Buildings and Structures, Tokyo, Japan, September, 1971, pp. 105-114.

466. Meroney, R.N., and Plate, E.J., "Wind-Tunnel Investigation of Shapes for Balloon Shelters", Journal of Applied Meteorology, Vol. 11, No. 5, August, 1972, pp. 849-857.

467. Millikan, C.B., "Advanced Education and Academic Research in Aeronautics", J.R., Aero.Soc., Vol. 61, 1957, pp. 793-808.

468. Milne-Thomson, L.M., Theoretical Hydrodynamics, 5th Ed., McMillan, 1968, pp. 200.

469. Minorsky, A.N., Nonlinear Oscillations, D. Van Nostrand, Inc., Princeton, 1962, pp. 353-355.

470. Minorsky, A.N., Introduction to Non-Linear Mechanics, J.W. Edwards, Ann Arbor, Mich., 1947, pp. 342-350.

471. Miyata, T., Kubo, Y., and Ito, M., "Analysis of Aeroelastic Oscillations of Long-Span Structures by Nonlinear Multidimensional Procedures", Proc. Fourth Int'l. Conf. on Wind Effects, London, England, September, 1975.

472. Mochizuki, M., "Smoke Observation on Boundary Layer Transition Caused by a Spherical Roughness Element", J. Phys. Soc. Jap., Vol. 16, 1961, pp. 995.

473. Mochizuki, M., "Hot-Wire Investigations of Smoke Patterns Caused by a Spherical Roughness Element", Nat. Sci. Rept., Ochanomizu Univ., Vol. 12, 1961, pp. 87.

474. Modi, V.J., and El-Sherbiny, S., "Effect of Wall Confinement on Aerodynamics of Stationary Circular Cylinders", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, II, 19, September, 1971, 11pp.

475. Modi, V.J., and Dikshit, A.K., "Mean Aerodynamics of Stationary Elliptic Cylinders in Subcritical Flow", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, II, 17, September 1971, 11p.

476. Modi, V.J., and Slater, J.E., "Quasi-Steady Analysis of Torsional Aeroelastic Oscillators", IUTAM/IAHr Symposium on Flow-Induced Structural Vibrations, Paper D2, August, 1972.

477. Mode, V.J., and Wiland, E., "Unsteady Aerodynamics of Stationary Elliptoc Cylinders in Subcritical Flow", AIAA Paper No. 69-745, July, 1969.

478. Moll, H.G., "Die Atmosphaerische Umstroemung Madeiras", Betir. Phys. Atmos., Vol. 44, 1971, pp. 227-244.

479. Monin, A.S., "Turbulence in the Atmospheric boundary Layer", The Physics of Fluids Supplement, Vol. 10, Part II of Two Parts, No. 9, Proceedings of International Symposium on Boundary Layers and Turbulence with Geophysical Applications, Tokyo, Japan, September, 1966, 1967, pp. 531-537.

480. Monin, A.S., and Obukhov, A.M., "Basic Laws of Turbulent Mixing in the Ground Layer of the Atmosphere", Trudy Geofizs. Inst. An SSSR, Vol. 2, No. 24, 1954, pp. 163-187.

481. Monin, A.S., and Yaglom, A.M., Statistical Fluid Mechanics, Translated by Lunley, J.L., M.I.T. Press, Cambridge, Mass., 1971.

482. Moore, D.W., "The Flow Past a Rapidly Rotating Cylinder in a Uniform Stream", Journal of Fluid Mechanics, Vol. II, Part 6, 1957, pp. 541.

483. Moore, F.K., "Lift Hysteresis at Stall as an Unsteady Boundary Layer Phenomenon", NACA Tech. Note No. 3571, 1955.

484. Moore, F.K., "Aerodynamic Effects of Boundary Layer Unsteadiness", Proc. 6th Anglo-American Aeronautical Conf. Roy. Aero. Soc. and Inst. Ae. Sci., 1957, pp. 439-476.

485. Moore, F.K., "On the Separation of the Unsteady Laminar boundary Layer", Proc. Int. Un. Theo. Appl. Mech., Freiburg, 1957, H. Gortler, ed., Springer-Verlag, 1958, pp. 296-311.

486. Morkovin, M.V., "Flow around Circular Cylinder---A Kaleidoscope of Challenging Fluid Phenomena", Symposium on Fully Separated Flows, Philadelphia, 1964, pp. 102-118.

487. Morkovin, M.V., "Transition from Laminar to Turbulent Shear Flows, A Review of the Recent Advances in its Understanding", Trans. ASME, Vol. 80, pp. 1121.

488. Morkovin, M.V., Nagib, H.M., and Yung, J.T., "On Modeling of Atmsopheric Surface Layers by the Counter-Jet Technique---Preliminary Results", Tech. Rept. AFSPR-TR-73-0592, Illinois Institute of Technology, Chicago, Ill., 1972.

489. Morton, B.R., "Geophysical Vortices", Progress in Aeronautical Sciences, Vol. 7, 1966.

490. Mujumdar, A.S., and Douglas, W.J.M., "Vortex Shedding from Slender Cylinders of Various Cross Sections", J. Fluids Engr., Trans. ASME, 1973, pp. 474-476.

491. Mukhopadhyay, V., "Wind Excited Vibration of Square Section Beam and Suspended Cable", Aeroelastic and Structures Research Laboratory, M.I.T., May, 1972.

492. Myerscough, C.J., "Further Studies of the Growth of Wind-Induced Oscillations in Over Head Lines", Journal of Sound and Vibration, Vol. 39, Part 4, 1975, pp. 503-517.

493. McDaniels, W.N., "An Analysis of Galloping Electric Transmission Lines", Trans. IEE, Vol. 79, 1960, pp. 406-412.

494. McGregor, D.M., "An Experimental Investigation of the Oscillating Pressure on a Circular Cylinder in a Fluid Stream", University of Toronto, Inst. of Aerophysics, UTIA Technical Note No. 14, 1957.

495. McKillop, J.A., "Wind Effects on Buildings and Structures", Proc. Int. Res. Seminar, Ottawa, Vol. 1, 1968, pp. 371-398.

496. KcKown, J.S., and Keulegan, G.H., "Vortex Formation and Resistance in Periodic Motion", Proc. ASCE, Vol. 85, No. EMI, January, 1959.

497. Nakaguchi, H., Hashimoto, K., and Muto, S., "An Experimental Study in Aerodynamic Drag of Rectangular Cylinders", J. Japan Soc. Aero. and Space Sciences, Vol. 16, 1968, pp. 168.

498. Nakamura, Y., "Vortex Excitation of a Circular Cylinder Treated as a Binary Flutter", Reports of Res. Inst. App. Mech., Kyushu U., Vol. XVII, No. 59, 1969.

499. Nakamura, Y., Kaku , S., and Mizota, T., "Effect of Mass Ratio on the Vortex Excitation of a Circular Cylinder", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, IV, 9, September, 1971, 10pp.

500. Nakamura, Y., and Mizota, T., "Galloping and Vortex Excitation of a Rectangular Block", Reports of Research Institute of Applied Mechanics, XIX, Vol. 64, 1972.

501. Nakao, Y., Yamashita, M., Takano, S., "Wind Induced Vibration of Tower of Suspension Bridge Under Construction", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, IV, 21, September, 1971, 10pp.

502. Narita , N.,"Wind Resistant Design of A Bridge Member with A H-Shaped Cross Section", Annual Report of Roads, Japan Road Association, 1974.

503. Narita, N., and Yokoi, M., "Wind Resistablility of Bridge Members", Roads, January, 1973.

504. Nash, J.F., "A Discussion of Two-Dimensional Turbulent Base Flow", Aero. Res. Coun. R & M No. 3468, 1967.

505. Naudascher, E., "Flow-Induced Structural Vibrations", Proc. IUTAM-IAHR Symposium, Karlsruhe, Springer-Verlag, Berlin , 1974.

506. Naudascher, E., "From Flow Instability to Flow-Induced Excitation", Proc. ASCE, Hy 4, July, 1967, pp. 15-40.

507. Naumann, A., Morsbach, M., and Kramer, C., "The Conditions of Separation and Vortex Formation Past Cylinders", AGARD Conf. Proc., Vol. 4, 1966, pp. 539-574.

508. Naumann, A., and Pfeiffer, H., "Uber die Grenzschichtablosung am Zylinder bei Hohen Geschwindigkeiten", Advances in Aeron. Sci., Vol. 3, Pergamon Press, 1962, pp. 185.

509. Naumann, A., and Quadflieg, H., "Vortex Generation on Cylindrical Buildings and Its Simulation in Wind Tunnels", IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August, 1972.

510. Newberry, C.W., Eaton, D.J., and Mayne, J.R., "Wind Pressure and Strain Measurements, at the Post Office Tower", Building Research Establishment, Current Paper 30/73, Garston, Watford, 1973, 35pp.

511. Nicholson, F.H., and Johnson, D.R., "A New Vortex Model Based on a Zero Laplacian of Vorticity", Tech. Report under NSF Grant GA-30978X, Dept. of Meterology, Univ. of Wisconsin, Madison, Wis., March, 1973, 64pp.

512. Nielson, K.T.W., "Vortex Formation in a Two-Dimensional Periodic Wake", Thesis submitted for Ph.D. Degree, Univ. of Oxford, Dept. of Eng. Sci., 1970, 114pp.

513. Nokkentved, C., "Wind Pressure on Buildings", Publ. Int. Assoc. Bridge and Structural Engrg., Vol. I, 1932, pp. 365, Vol. II, 1934, pp. 257.

514. Nokentved, C., "Variation of the Wind-Pressure Distribution on Sharp-Edged Bodies", Laboratorium for Bygningasstatik, Denmard Tekniske Hojskole, 1936, and SC-4204.

515. Nokkentved, C., "Vibrations Produced by Wind", Dansk Selskab for Bygningsstatik, Copenhagen, Denmark, 1941.

516. Nokkentved, C., and Flensborg, C.E., Fortsatte Laevirkningsunders gelser, Hedeselskabets Tidskrift, Denmark, 1940.

517. "Normen Fur die Nelastungsannahmen, die Inbetriebnahme und die Uberwachung der Bauten", Schweizerischer Ingenieur - und Architekten - Verin, NR. 160, 1956.

518. Novak, M., "Aeroelastic Galloping of Rigid and Elastic Bodies, Research Report, University of Western Ontario, Faculty of Engineering Science, London, Ontario, Canada, March, 1968.

519. Novak, M., "Uber winderregate Querschwingungen der Stander der Bogenbrucke uber die Moldau", Der Stahlbau, Heft 11, 1968.

520. Novak, M., "Aeroelastic Galloping of Prismatic Bodies", Proc. ASCE, EMI, February, 1969, pp. 115-142.

521. Novak, M., and Davenport, A.G., "Aeroelastic Instability of Prisms in Turbulent Flow", Proc. ASME, EMI, February, 1970, pp. 17-39.

522. Novak, M., "Galloping and Vortex-Induced Oscillations of Structures", Proc. Third Intl. Conf. Wind Effects on Bldg, and Struc., Tokyo, Japan, 1971.

523. Novak, M., "Galloping Oscillations of Prismatic Structures", Proc. ASCE, February, 1972, pp. 27-46.

524. Novak, J., "Strouhal Number and Flat Plate Oscillation in an Air Stream", ACTA Tech., CSAV Vol. 18, 1973, pp. 372-380.

525. Ohkuma, T., and Fujimoto, M., "An Analysis of Aeolian Vibration of Circular Cylinder", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, IV, 8, September, 1971, 10pp.

526. Okamoto,T., and Yagita, M., "The Experimental Investigation on the Flow Past a Circular Cylinder of Finite Length Placed Normal to the Plane Surface in Uniform Stream", Bull. JSME, Vol. 16, 1973, pp. 805-814.

527. Okubo, T., and Narita, N., "Wind Induced Oscillation of Bridge Members", 3rd Joint Meeting U.S. - Japan Panel on Wind and Scismic Effects, Tokyo, Japan, May, 1971.

528. Okubo, T., Narita, N., and Yokoyama, K., "Some Approaches for Improving Wind Stability of Cable-Stayed Girder Bridges", Proc. Fourth Int'l Conf. on Wind Effects, London, England, September, 1975.

529. Okubo, T., and Narita, N., "Wind Tunnel Test Report on the Suehiro Bridge", Chiba Branch, Japan Public Works Research Institute, March, 1973.

530. Okubo, T., Okauchi, I., and Murakami, E., "Aerodynamic Response of a Large-Scale Bridge Model Against Natural Wind", Paper, Symposium on Full-Scale Measurements of Wind Effects on Tall Buildings and Other Structures, London, Ont., Canda, 23-29, June, 1974.

531. O'Neill, P.G.G., "Experiments to Simulate a Natural Wind Gradient in the CAT", NPL/Aero/313, 1956.

532. Ostenfeld, C., Haas, G., and Frandsen, A.G., "Motorway Bridge Across Lillebaelt", Proc. Symposium on Suspension Bridges, Lisbon, Portugal, November, 1966.

533. Ostrowski, J.S., Marshall, R.D., and Cermak, J.E., "Vortex Formation and Pressure Fluctuations on Buildings", Proc. of International Seminar on Wind Effects on Buildings and Structures, Ottawa, Canada, September, 1967, pp. 459-484.

534. Otsuki, Y., Washizu, K., Tomizawa, H., Ohya, A., and Fujii, K., "Experiments on the Aeroelastic Instability of Prismatic Bars with Rectangular Sections", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, IV, 24, September, 1971, 8pp.

535. Owens, P.R., "Buffeting Excitation of Boiler Tube Vibration", Journal of Mechanical Engineering Science, Vol. 7, No. 4, 1965, pp. 341-439.

536. Ozker, M.S., and Smith, J.C., "Factors Influencing the Dynamic Behavior of Tall Stacks under the Action of Wind", Trans. ASME, Vol. 78, No. 6, 1956.

537. Packer, M.A., Wind Pressure Measurements on the Surfaces of Three Shapes of Roof Ventilators, NPL/Aero/1077, 1962.

538. Page, J.K., Field Investigations of Wind Failures in the Sheffield Gales of 1962, Loughborough University, 1968.

539. Pagon, W.W., "Aerodynamics and the Civil Engineer", Engineering News-Record, Vol. 112, 1934, pp. 348; Vol. 113, 1934, pp. 41, 456, 814; Vol. 114, 1935, pp. 582, 665, 742; Vol. 115, 1935, pp. 601.

540. Pagon, W.W., "Wind Forces on Structures: Plate Girders and Trusses", Proc. Paper No. 1711, ASCE, Vol. 84, No. ST4, July, 1958.

541. Pagon, W.W., "Closure to 'Wind Forces on Structures: Plate Girders and Trusses'", Proceedings ASCE, Vol. 85, No. ST7, September, 1959.

542. Paidoussis, M.P., "An Experimental Study of Vibration of Flexible Cylinders Induced by Nominally Axial Flow", Nucl. Sci. & Eng., Vol. 35, 1969, pp. 127- 138.

543. Panofsky, H.A., "The Atmospheric Boundary Layer Below 150 Meters", Annual Reviews of Fluid Mechanics, Vol. 6, 1974, pp. 147-177.

544. Panofsky, H.A., and McCormick, R.A., "The Spectrum of Vertical Velocity near the Surface", Quart. J. Royal Meteorological Soc., Vol. 86, 1960.

545. Pao, Y.H., et. al., "Vortex Streets in Stably Stratified Fluids", Boeing BSRL D 1-82-0736, 1968.

546. Parker, R., "Resonance Effects in Wake Shedding from Parallel Plates: Calculation of Resonant Frequencies", J. Sound Vib., Vol. 5, 1967, pp. 330.

547. Parkinson, G.V., "Wind-Induced Instability of Structures", Phil. Trans. Roy. Soc., London A, Vol. 269, 1971, pp. 395-409.

548. Parkinson, G.V., "Mathematical Models of Flow-Induced Vibrations of Bluff Bodies", Proceedings of IUTAM-IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Springer Verlag, Berlin, 1972.

549. Parkinson, G.V., "Aeroelastic Galloping in One Degree of Freedom", Proc. Symp. Wind Effects on Bldg. and Struc., Teddington, England, 1963, pp. 581-609.

550. Parkinson, G.V., "Aspects of the Aeroelastic Behavior of Bluff Cylinders", Engr. Inst. Canada, 6, Paper No. EIC-63-Mech., Vol. 2, 1963.

551. Parkinson, G.V., and Brooks, N.P.H., "On the Aeroelastic Instability of Bluff Cylinders", J. Appl. Mech., Vol. 28, 1961, pp. 252-258.

552. Parkinson, G.V., Feng, C.C., and Ferguson, N., "Mechanisms of Vortex-Excited Oscillations of Bluff Cylinders, Paper 27, Symp. Wind Effects on Buildings and Structures, Loughborough, England, April, 1968.

553. Parkinson, G.V., and Smith, J.D., "The Square Prism as an Aeroelastic Nonlinear Oscillator," Q. J. Mech. Appl. Math. IXII (2), 1964, pp. 225-239.

554. Parkinson, G.V., and Smith, J.D., "An Aeroelastic Oscillator with Two Stable Limit Cycles," ASME Trans., J.A.M., June, 1962.

555. Patton, K.T., "Flow Patterns Around a Circular Cylinder", USL Technical Memoradum No. 933-361-64, November, 1964.

556. Paulhamus, E.C., "Effect of Flow Incidence and Reynolds Number as Low-Speed Aerodynamic Characteristies of Several Noncircular Cylinders with Application to Defectional Stability and Spinning", NASA, TR R29, 1959.

557. Pechstein, W., "Dor Naturlichen Wind und Seine Wirkung auf einen Grosseren Kreiszylinder", Dissertation Tech. Hochschule Hannover, reported by A. Proll, 1942, Z Ver dtsch. Ing., Vol. 86, 1940.

558. Penwarden, A.D., "Acceptable Wind Speeds in Towns", Building Science, Vol. 8, No. 3, September, 1973, pp. 259-267.

559. Penzien, J., "Wind Induced Vibration of Cylindrical Structures", Proc. Paper No. 1141, ASCE, Vol. 83, No. EM1, January, 1957.

560. Pestel, E.C. and Leckie, F.A., Matrix Methods in Elasto-Mechanics, London: McGraw-Hill Book Company, 1963.

561. Peterka, J.A., and Cermak, J.E., "Wind-Engineering Study of the Federal Reserve Bank Building, Richmond", Fluid Dynamics and Diffusion Laboratory, Technical Report CER73-74JAP-JEC8, Colorado State University, Fort Collins, Colo., 1973.

562. Peterka, J.A., and Cermak, J.E., "A Wind Model for an Elevated STOL-Port Configuration", NASA CR-2450, National Aeronautics and Space Administration, Washington, D.C., July, 1974, 39pp.

563. Peterka, J.A., and Cermak, J.E., "Probability Distributions of Wind Pressure Fluctuations on Buildings", Paper Presented at ASCE Specialty Conference on Probabilistic Methods in Engineering, Stanford University, Palo Alto, California, June, 1974, 15pp.

564. Peterka, J.A., and Cermak, J.E., "Simulation of Atmospheric Flows in Short Wind Tunnel Test Sections", Fluid Dynamics and Diffusion Laboratory, Tech. Rept. CER73-74JAP-JEC32, Colorado State University, Fort Collins, Colo., 1974, pp. 52.

565. Peterka, J.A., and Richardson, P.D., "Effects of Sound on Separated Flows", Journal of Fluid Mechanics, Vol. 37, Part II, 1969, pp. 265-287.

566. Peterson, J.B., and Horton, E.A., "An Investigation of a Highly Favorable Pressure Gradient on Boundary Layer Transition as Caused by Various Types of Roughnesses on a 10-Foot Diameter Sphere", NASA Memo, 2/8/59L, 1959.

567. Petrie, A.M., "Effect of Free Stream Turbulence on Vortex Shedding in the Wake of Cylinders in Cross-Flow", J. Sound & Vibration, Vol. 34, No. 2, May, 1974, pp. 287-290.

568. Pfenninger, W., "Transition Experiments in the Inlet Length of Tubes at High Reynolds Numbers, Appendix of Boundary Layer Suction Experiments with Laminar Flow at High Reynolds Numbers", Boundary Layer and Flow Control, G.V. Lachmann, ed., Pergamon Press, Vol. 2, 1961, pp. 970-980.

569. Phillips, O.M., "The Intensity of Aeolian Tones", J. Fluid Mech., Vol. 1, 1956, pp. 607-624.

570. Phillips, W.H., "Theoretical Analysis of Oscillations of a Towed Cable", NACA TN 1796, 1949.

571. Peirce, D., "Photographic Evidence of the Formation and Growth of Vorticity hehind Plates Accelerated from Rest in Still Air", J. Fluid Mech., Vol. 11, November, 1961, pp. 460-464.

572. Piercy, N.A.V., and Richardson, E.G., "The Turbulence in Front of a Body Moving Through a Viscous Fluid", Phil Mag., Vol. 9, 1930, pp. 1038.

573. Polachek, M., Waltum, R., and Dawson, C., "Transient Motion of an Elastic Cable Immersed in a Fluid", Mathmatics of Computation, January, 1963, pp. 60-63.

574. Powell, A., "On the Edgetone", J. Acoust. Soc. Am., Vol. 33, Part 4, 1961, pp. 359-409.

575. Prandtl, L., "Uber Flussigkeitsge egung Bei sehr Kleiner Reibung", Proc. 3rd Intern. Math. Congr., Heidelberg, 1904.

576. Prandtl, L., "Meteorologische Anwendung der Stromungslehre", Beitrage zur Physik der Freien Atmosphure, Vol. 19, 1932, pp. 188.

577. Prandtl, L., and Betz, A., "Ergehbisse der Aerodynamischen Vershuchsanstalt (A VA) zu Geottingen", Vol. I, 1920, Vol. II, 1923, Vol. III, 1927, Vol. IV, 1932, Berlin.

578. Prandtl, L., and Reichardt, H., "Einfluss von Warmeschichtung aur Eigenschaften einer turbulenten Stromung", Deutsche Forschung, No. 21, Berlin, 1934, pp. 110-121.

579. Prandtl, L., and Tietjens, O.G., Applied Hydro and Aero-mechanics, Trans. by J.P. den Hartog, McGraw-Hill Book Co., Inc., New York, 1934.

580. Prendergast, V., "Measurement of Two-Point Correlations of Velocity Near a Circular Cylinder Shedding a Karman Vortex Street", University of Toronto, UTIA Tech. Note 31, January, 1960.

581. Pretsch, J., "Die Anfachung Instabiler Storungen in einer Laminaren Reibungsschicht", Jahrbuch Deutsch, Luftfahrtforschung, I., 1942, pp. 54, NACN Translation Tech. Memo. No.1343, 1952.

582. Price, P., "Suppression of the Fluid-Induced Vibration of Circular Cylinders", Proc. Paper No. 1030, ASCE, V 82, No. EM3, July, 1956.

583. Pris, R., "L'Action du Vent Sur Les Batiments et Constructions", Trav. Architect. Construct., Vol. 20, 1936, pp. 71.

584. Protos, A., Goldschmidt, V.W., and Toebes, G.H., "Hydroelastic Forces on Bluff Cylinders", Journal of Basic Engineering, Trans. ASME, Series, D., Vol. 90, Bo. 3, May, 1968, pp. 378-386.

585. Raggett, J.D., Modeling Problems in the Study of Bridge Flutter, Princeton University, 1971.

586. Ramamurthy, A.S., Subramanya, K., and Souriyal, N., "Vortex Shedding Characteristics of Eccentrically Mounted Prisms", Aeronautics J., Vol. 79, No. 769, January, 1975, pp. 42-44.

587. Ramberg, S.E., and Griffin, O.M., "Vortex Formation in the Wake of a Vibrating, Flexible Cable", Trans. ASME, J. Fluids Eng., Vol. 96, 1974, pp. 317-322.

588. Ramberg, S.E., and Griffin , O.M., "Some Transverse Resonant Vibration Characteristics of Wire Rope with Application to Flow-Induced Cable Vibrations", Naval Research Laboratory Formal Report 7821, 1974.

589. Ramberg, S.E., and Griffin, O.M., "Velocity Correlation and Vortex Spacing in the Wake of a Vibrating Cable", Trans. ASME, J. Fluids Engr., 1975.

590. Ramsey, J.P., and Dillon, D.B., "Empirical Hydrodynamic Characterization of Two Bare Double-Armored Towlined", HRC Report No. 293, November, 1970.

591. Rao, C.K., "Nonlinear Torsional Vibrations of Thin-Walled Beams of Open Section", Trans. of the ASME, March, 1975, pp. 240-242.

592. Rao, C.K., and Satyam, A.A., "Torsional Vibrations and Stability of Thin-Walled Beams on Continous Elastic Foundation", AIAA Journal, Vol. 13, No. 2, February, 1975.

593. Rathburn, J.C., "Wind Forces on a Tall Building", Trans. ASCE, Vol. 105, 1940, pp. 1.

594. Ratkowskim, J.J., "Experiments with Galloping Spans", IEEE Trans. Power App. and Syst., Vol. 87, 1968, pp. 1385-1393.

595. Raymer, W.G., Nixon, H.L., and Maybrey, J.F.M., Tests on Callender's Television Mast in the Duplex Wind Tunnel, NPL/Aero/268, 1954.

596. Reed, W.H., "Ground Wind Load Considerations for Space Shuttle Vehicles", Space Transportation System Technology Symposium Vol. II, 1970.

597. Reinhold, T.A., Tieleman, H.W., and Maher, F.J., "Investigation of a Grid-Induced Turbulent Environment for Wind Tunnel Testing, Report VPI-E-74-30, Dept. Eng. Sci., Virginia Polytech. Inst., Blacksburg, Va., December, 1974.

598. Relf, E.H., and Powell, C.H., "Tests on Smooth and Stranded Wires Inclined to the Wind Direction and a Comparison of the Results on Stranded Wires in Air and Water", British ARC, R & M, 1917.

599. Relf, E.H., and Simmons, L.F.G., "The Frequencies of the Eddies Generated by the Motion of Circular Cylinders Through a Fluid", Aeronautical Research Com. R. & M., No. 917, June, 1924.

600. Report of the Committee of Inquiry into Collapse of Cooling Towers at Ferrybridge, November, 1965.

601. Reudy, R., "Vibrations of Power Lines in a Steady Wind", Canadian Journal of Research, October, 1935.

602. Riabouchinsky, D., "On Some Cases of Two-Dimensional Fluid Motion", Proc. London Math. Soc., Vol. 25, 1926, pp. 185-194.

603. Richards, D.T.W., "Aerodynamic Properties of Savern Crossing Conductors", Paper No. 8, Ref. 1, Conf. Wind Effects on Bldg. and Structures, 1963.

604. Richardson, A.S., and Martuccelli, J.R., "Research Study on Galloping Electric Power Transmission Lines", M.I.T., Aeroelasti and Structures Research Laboratory, Progress Report No. 1-6, 1960-1961.

605. Richardson, A.S., Martucelli, J.R., and Price, W.S., "Research Study on Galloping of Electric Power Transmission Lines", N.P.L. Symposium, H.M.S.O., 1965.

606. Richardson, A.S., and Martuccelli, J.R., "An Investigation of Galloping Transmission Line Conductors", IEEE Trans. Paper No. 63-1029, 1963.

607. Richardson, A.S., and Martuccelli, J.R., A Proposed Solution to the Problem of Galloping Conductors", IEEE Conference Paper No. C.P. 64-46, 1964.

608. Richardson, A.S., and Martuccelli, J.R., "A Further Investigation of Galloping Transmission Line Conductors", IEEE Conference Paper No. C.P., 64-45, 1964.

609. Richardson, L.R., "The Supply of Energy from and to Atmospheric Eddies", Proc. Roy. Soc. of London, Vol. 97, 1920, pp. 354.

610. Roberts, G., "The Severn Bridge --- A New Principle of Design", Proc. Symposium on Suspension Bridges, Lisbon, Portugal, November, 1966.

611. Roberts, J.B., "A Linear Theory for the Fluctuating Drag of Simple Structures in Turbulent Flow", Nat. Phys. Lab. NPL Aero. Rep. 1329, March, 1971, 23pp.

612. Rosenbrook, G., "Instabilitat der Gleitschicht im Schwach Divergenten Kanl", Zeit. f. Angew. Mech. Math., Vol. 17, 1937, pp. 8.

613. Rosenbrock, H.H., and Tagg, J.R., "Wind and Gust-Measuring Instruments", Proc. I.E.E., Paper No. 1065, 1951.

614. Rosenhead, L., "Vortex Systems in Wakes", Advances in Applied Mechanics, Vol. III, Academic Press, New York, pp. 185-195.

615. Roshko, A., "On the Drag and Shedding Frequency of Two-Dimensional Bluff Bodies", Nat. Adv. Comm. Aero., Wash., Tech. Note 3169, July, 1954, 29pp.

616. Roshko, A., "On the Development of Turbulent Wakes from Vortex Sheets", NACA Tech. Report 1191, 1954.

617. Roshko, A., "Experiments on the Flow Past a Circular Cylinder at Very High Reynolds Number", Journal of Fluid Mechanics, Vol. 10, 1961, pp. 345-356.

618. Roshko, A., "On the Wake and Drag of Bluff Bodies", J. of Aero. Sciences, February, 1955, pp. 124.

619. Roshko, A., "On the Aerodynamic Drag of Cylinders at High Reynolds Numbers", Proc. of Seminar on Wind Loads on Structures, University of Hawaii, Honolulu, Hawaii, October, 1970, pp. 87-98.

620. Roshko, A., "A New Hodograph for Fress Streamline Theory", NACA TN 3168, July, 1954.

621. Roshko, A., "A Review of Concepts in Separated Flow", Proc. 1st Canadian Congress Appl. Mech., Vol. 3, 1967, pp. 81-115.

622. Roshko, A., (ed), "Wind Loads on Structures", Summary Report on a Conference Held at the California Institute of Technology, Pasadena, California, December, 1970, 137pp.

623. Roshko, A., and Lau, J.C., "Some Observations on Transition and Reattachment of a Free Shear Layer in Incompressible Flow", Proc. Heat Transfr. and Fluid Mech. Inst., Stanford, 1965, pp. 157-167.

624. Ross, D., Vortex-Shedding Sounds of Propellers, Bolt, Beranek and Newman, Inc., Report 1115, March, 1964.

625. Rossby, C.G., "A Generalization of the Theory of the Mixing Length with Applications to Atmospheric and Oceanic Turbulence", Meteorological Papers, Vol. I, No. 4, M.I.T., Cambridge, Mass., 1932, pp. 33.

626. Routh, E.J., Advanced Rigid Dynamics, MacMillian Book Co., New York, N.Y., 1905.

627. Rouse, H., "Model Techniques in Meteorological Research", Composium of Meteorology, American Meterorological Society Boston, 1951, pp. 1249-1254.

628. Ruark, A.E., "Inspectional Analysis, 'A Method which Supplements Dimensional Analysis'", Journal Elisha Mitchell Science Society, Vol. 51, 1935, pp. 127-133.

629. Ruedy, R., "Vibrations of Power Lines in a Steady Wind", Canadian Journal of Research, Vol. 13, Sec. A., 1935, pp. 82.

630. Ruscheweyh, H., "Flue Gas Concentrations in the Effect Range of a Power Plant, as Investigated in the Wind Tunnel with the Aid of a Model", Staub-Reinhalt-Luft, Vol. 31, No. 5, May, 1972, pp. 11-20.

631. Ryan, R., "Experiments on Aerodynamic Cooling", Sc.D. Thesis, Inst. of Tech., Zurich, 1951.

632. Sabzevari, A., and Scanlan, R.H., "Aerodynamic Instability of Suspension Bridges", Proc. ASCE, J. Eng. Mech. Div., April, 1968, pp. 489-519.

633. Sachs, P., Wind Forces in Engineering, Pergamon Press, 1972.

634. Sadeh, W.Z., and Ceramk, J.E., "Turbulence Effects on Wall Pressure Fluctuations", Journal of Engineering Mechanics, ASCE, Vol. 98, No. EM6, 1972, pp. 1365-1379.

635. Sadeh, W.Z., Suters, S.P., and Maeder, P.F., "An Investigation of Vorticity Amplification in the Flow Apporaching a Two-Dimensional Stagnation Point", Z. Agnew. Math. Phys., Vol. 21, 1970, pp. 699-742.

636. Sainsbury, R., and King, N., "The Flow-Induced Oscillations of Mar ne Structures", Proc. Instn, Civil Engrs., Vol. 49, 1971, pp. 269-302.

637. Sallet, D.W., "On the Self Excited Vibrations of a Circular Cylinder in Uniform Flow", Shock and Vibration Bulletin, Vol. 40, Part 3, 1969.

638. Sallet, D.W., "On the Reduction and Prevention of the Fluid-Induced Vibrations of Circular Cylinders of Finite Length", Shock and Vibration Bulletin, Vol. 41, Part 6, 1970, pp. 31.

639. Sallet, D.W., "Suppression of Flow-Induced Vibrations by Means of Body Surface Modifications", Shock and Vibration Bulletin, Vol. 42, Part 4, 1972, pp. 215-228.

640. Sallet, D.W., "On the Spacing of Karman Vortices", J. Appl. Mechanics, Trans. ASME, Vol. 36, 1969, pp. 370-372.

641. Sallet, D.W., "On the Prediction of Flutter Forces", IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August, 1972.

642. Salter, C., and Raymer, W.G., Pressure Measurements at a High Reynolds Number on a Model Cooling Tower Shielded by a Second Tower, NPL/Aero/1027, 1962.

643. Samras, R.K., Skop, R.A., and Milburn, D.A., "An Analysis of Coupled Extensional-Torsional Oscillations in Wire Rope", Trans. ASME, November, 1974, pp. 1130-1135.

644. Santosham, T.V., "Force Measurements on Bluff Cylinders and Aeroelastic Galloping of a Rectagular Cylinder", M.A.Sc. Thesis, U. British Columbia, 1966.

645. Sanuki, M., Kimura, S., and Tsunda, N., "Studies on Biplane Wind Vanes, Ventilator Tubes and Cup Anemometers", Pap. Met. Geophys., Tokyo, II, 1951.

646. Sarojatam, T., "An Analytical Study of Separated Flow about Circular Cylinders", Proc. Symp. Unsteady Flow., American Society of Mechanical Engineers, 1968.

647. Sarpkaya, T., "An Analytical Study of Separated Flow about Circular Cyinders", ASME Paper No. 68-FE-36, 1968.

648. Savkar, S.D., "Oscillations of Cylindrical Rods and Cables in Shear Flows", J. Sound Vib., Vol. 16, Part 2, 1971, pp. 161-172.

649. Saw, T.L., and Chaplin, J.R., "On the Mechanics of Flow Induced Periodic Forces on Structures Dynamic Waves in Civil Engineering", Howells, D.A., Haigh, I.P., and Taylor, C., (ed), Wiley-Interscience, 1971.

650. Sawyer, R.A., "Torsional Stability of H Sections in Random Vertical Gusts", Paper Presented at IUTAM-IAHR Symp. on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper D6 August, 1972, 5pp.

651. Scanlan, R.H., "An Examination of Aerodynamic Response Theories and Model Testing Relative to Suspension Bridges", Proceedings of the Third International Conference on Wind Effects on Buildings and Structures, Tokyo, Japan, 1971, pp. 941-951.

652. Scanlan, R.H., "Studies of Suspension Bridge Deck Flutter Instability", AIAA Paper 69-744, AIAA Subsonic Aerodynamics Meeting, Ottawa, 1969.

653. Scanlan, R.H., "Analytical Models of Suspension Bridge Response to Wind for Use in Reliability Studies", Reliability Approach in Structural Engineering, Maruzen Co. Ltd., Tokyo, 1975, pp. 299-314.

654. Scanlan, R.H., Belivieau, J-G, and Budlong, K.S., "Indicial Aerodynamic Functions for Bridge Decks", Proc. ASCE, J. Eng. Mech. Div., August, 1974, pp. 657-672.

655. Scanlan, R.H., "The Suspension Bridge: Its Aeroelastic Problems", Paper 71-Vibr.-38 ASME Vibrations Conference, Toronto, September, 1971.

656. Scanlan, R.H., "Aeroelastic Stability of Long-Span Bridges Theoretical Considerations", Report Presented at Federal Highway Administration Region 9 Progress Review (Category IV) San Francisco, Calif. September, 1973.

657. Scanlan, R.H., and Sabzevari, A., "Suspension Bridge Flutter Revisited", Paper 468, ASCE Structural Engineering Conference, Seattle, Washington, May, 1967.

658. Scanlan, R.H., and Sabzevari, A., "Experimental Aerodynamic Coefficients in the Analytical Study of Suspension Bridge Flutter", J. Mech. Eng. Sci., 11, 3, June, 1969, pp. 234-242.

659. Scanlan, R.H., and Tomko, J.J., "Airfoil and Bridge Deck Flutter Derivatives", J. Engrg. Mech. Div., ASCE, December, 1971, pp. 171-1737.

660. Schmidt, L.V., "Measurement of Fluctuating Air Loads on a Circular Cylinder", Proc. AIAA Fifth Annual Structures and Materials Conference, Palm Springs, April, 1964.

661. Schmidt, L.V, Fluctuating Force Measurements Upon a Circular Cylinder at Reynolds Numbers Up to 5 x 10^6, NASA Langley Res. Center, June, 1966.

662. Schwabe, M., "Ueber Druckermittlung in der Michtstationaren Ebenen Stromung", Ingerieur-Archiv., Vol. 6, 1935.

663. Scruton, C., "On the Wind-Induced Oscillations of Towers, Stacks, and Masts", Proc. Symposium on Wind Effects on Structures, Teddington, (UK), 1963.

664. Scruton, C., "Wind-Excited Oscillations of Structures", Proc. Inst. of Civil Engineers, Vol. 27, 1964, pp. 673-702.

665. Scruton, C., "Aerodynamic Buffeting of Bridges", The Engineer, Vol. 199, May, 1955, pp. 654-667.

666. Scruton, C., "A Note on a Device for the Suppression of the Vortex-Excited Oscillations of Flexible Structures of Circular or Near Circular Section with Special Reference to its Application to Tall Stacks", NPL Aero. Note, No. 1012, 1963.

667. Scruton, C., "Note on the Aerodynamic Stability of Truncated Circular Cones and Tapered Stacks", NPL/Aero/305.

668. Scruton, C., "The Use of Wind Tunnels in Industrial Aerodynamic Research", Report, 309, October, 1960.

669. Scruton, C., "An Experimental Investigation of the Aerodynamic Stability of Suspension Bridges",Proc. Third Congress, Int'l Ass'n for Bridge and Structural Engrg., 1948, pp. 463-473.

670. Scruton, C., and Gimpel, C., "Memorandum on Wind Structure with Reference to BS Code of Practice CP3". Chapter V, NPL/Aero/361.

671. Scruton, C., and Flint, A.R., "Wind-Excited Oscillations of Structures", Proc. Inst. Civ. Engineers, Vol. 27, 1964, pp. 673-702.

672. Scruton, C., and Newberry, C.W., "On the Estimation of Wind Loads for Building and Structural Design", Proc. Inst. Civ. Eng., Vol. 25, 1963, pp. 97-126.

673. Scruton, C., Whitbread, R.E.,and Charlton, T.M., "An Aerodynamic Investigation of a Tower Block", NPL/Aero/1032, 1964.

674. Scruton, C., and Rogers, E.W.E., "Steady and Unsteady Wind Loading of Buildings and Structures", Phil Trans. Roy. Soc., London, Series A. Vol. 269, 1971, pp. 353-383.

675. Scruton, C., and Walshe, D.E.J., "A Means for Avoiding Wind Sxcited Oscillations of Structures with Circular or Nearly Circular Cross Sections", NPL/Aero/335. October, 1957.

676. Sears, W.R.,"The Boundary Layer of Yawed Cylinders", Journal of Aeronautical Science, Vol. 15, 1948, pp. 49-52.

677. Sedrak, M., "Widerstandsmessungen am Schwingenden Zylinder bei Kleinen Reynolds-Zahlen", Dissertation TU Berlin, Fakultaet fuer Machinenwesen, 1970, 98pp.

678. Selberg, A., "Dampening Effects on Suspension Bridges", Int. Ass. Bridge and Struct. Eng. 10.

679. Selberg, A., "Aerodynamic Effects on Suspension Bridges", NPL. Symposium, Paper 11, H.M.S.O., 1965.

680. Selberg, A., and Hjorth-Hasen, E., "Aerodynamic Stability and Related Aspects of Suspension Bridges", Proc. Symposium on Suspension Bridges, Lisbon, Portugal, November, 1966.

681. Serrin, J., "The Swirling Vortex", Phil Trans. Royal Soc. London A, Vol. 271, No. 1214, January, 1972, pp. 325-360.

682. Sevik, M., "Lift on an Oscillating Body of Revolution", AIAA Journal, 2, 2, February, 1964, pp. 302-305.

683. Shair, F.H., Grove, A.S., Peterson, E.E., and Acrivos, A., "The Effect of Confining Walls on the Stability of the Steady Wake Behind a Circular Cylinder", J. Fluid Mech., Vol. 17, 1963, pp. 546.

684. Sharma, C.B., and John, D.J., "Wind-Induced Oscillations of Circular Cylindrical Shells: An Experimental Investigation", Department of Transport Technology, Loughborough University of Technology Report No. TT 7008, July, 1970.

685. Shaw, T.L., "On the Nature of Fluctuating Circulation Lift and Flow-Induced Structural Vibrations", J. Sound Vib., Vol.14, Part 2, 1971, pp. 251-261.

686. Shaw, T.L., "Steady Flow Past a Flat Plate in a Channel", J. Hyd. Div. Am. Soc. Civ. Engrs., Vol. 95, November, 1969.

687. Shears, M., "Problems in the Application of Statistical Design Methods", Preprints ot Ciria Seminar on The Modern Design of Wind-Sensitive Structures (London), Paper 7, June 1970, 8pp.

688. Shellard, H.C., "The Estimation of Design Wind Speeds", Proc. Conf. Wind Effects on Buildings and Structures, H.M.S.O., 1963.

689. Sherlock, R.H., "Variation of Wind Velocity and Gusts with Height", Transactions, ASCE, Vol. 118, 1953, pp. 463.

690. Sherlock, R.H., "Closure to 'Nature of the Wind'", Proceedings, ASCE, Vol. 86, No. ST7, July, 1960.

691. Sherlock, R.H., "Discussion by R.C. Gentry of 'Nature of the Wind'", Proceeding, ASCE, Vol. 85, No. ST3, March, 1959.

692. Sherlock, R.H., "Gust Factors for the Design of Buildings", Publications Vol. 8, Internatl. Assoc. for Bridge and Structural Engrg., Zurich, Switzerland, 1947.

693. Sherlock, R.H., and Lesher, E.J., "Design of Chimneys to Control Downwash of Gases", Trans. ASME, January, 1955, pp. 1-9.

694. Sherlock, R.H., and Stalker, E.A., "A Study of Flow Phenomena in the Wake of Smokestacks", Engr. Res. Bull. No. 29, University of Michigan, 1941, 49pp.

695. Sherwood, G.E., "Wood Structures Can Resist Hurricanes", Civil Engng. ASCE, Vol. 42, No. 9, September, 1972, pp. 91-94.

696. Shiller, L., and Linke, W., "Druck-und Reibungswiderstand des Zylinders bei Reynolds Sohen Zahlen 5000 bis 40000", N.A.C.A. Tech. Memo. 715, 1933.

697. Shinozuka, M., "Simulation of Multivariate and Multidimensional Random Processes", J. Accoust. Soc. of America, 49, 1, Part 2, January, 1971, pp. 357-368.

698. Shioiri, J., "Synchroniza ion Phenomenon in Vortex Shedding and its Role in Vortex Induced Oscillation of Structures", Proc. 3rd Int. Conf. Wind Effects on Buildings and Structures, Tokyo, 1971, pp. 677-686.

699. Shiraishi, N., "On Aerodynamic Responses of Truss-Stiffened Bridge Sections in Fluctuating Wind Flows", Paper Presented at IUTAM-IAHR Symp. on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August, 1972, 4pp.

700. Shiraishi, N., "An Investigation on Aerodynamic Responses of Plate-Like Structures in Fluctuating Gusts", Proc, 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, IV, September, 1971, 10pp.

701. di Silvio, G., "Self-Controlled Vibration of Cylinder in Fluid Stream", Proc. ASCE, EM2, April, 1969, pp. 347-361.

702. Simiu, E., "Gust Factors and Alongwind Pressure Correlations", J. Struct. Div. ASCE, 99, ST4, April, 1973, pp. 773-783.

703. Simiu, E., "Wind Spectra and Dynamic Alongwind Response", J. Struct. Div., ASCE, ST9, September, 1974, pp. 1897-1910.

704. Simiu, E., Buffeting and Aerodynamic Stability of Suspension Bridges in a Turbulent Wind, Doctoral Dissertation, Dept. of Civil Engineering, Princeton University, Princeton, N.J., March, 1974.

705. Simmons, L.G.F., and Cowdrey, C.F., "Measurements of the Aerodynamic Forces Acting on Porous Screens", NPL/Aero/2276, 1961.

706. Simon, W.E., "The Unsteady Surface Pressure Around Circular Cylinders in Two-Dimensional Flow", Wind Loads on Buildings and Structures, Nat. Sur. Stand. Building Science Series, Vol. 30, 1970, pp. 87-91.

707. Simpson, A., "Stability of Subconductors of Smooth Circular Cross-Section", Proc. Inst. Elect. Engrs., Vol. 17, Part 4, April, 1970, pp. 741-750.

708. Simpson, A., "Oscillations of Catenaries and Systems of Overhead Transmission Lines", Ph.D. Dissertation, Univ. Bristol, England, 1963.

709. Simpson, A., "Aerodynamic Instability of Long-Span Transmission Lines", Proc. IEE, Vol. 112, 1965, pp. 315-324.

710. Simpson, A., "Subconductor Oscillation: Summary of Results of Recent Research at the University of Bristol", Proc. IEE, Vol. 117, 1970, pp. 751-752.

711. Simpson, A., "Determination of the Natural Frequencies of Multiconductor Overhead Transmission Lines", J. Sound and Vib., Vol. 20, 1972, pp. 417-449.

712. Simpson, A., and Lawson, T.V., "Oscillations of 'Twin' Power Transmission Lines", Loughborough Symposium, Paper 25, 1968.

713. Singer, I.A., Wind Gust Spectra, Annals, N.Y. Acad. Sci., Vol. 116.

714. Sisto, F., "Stall Flutter in Cascades", J. Aero. Sci., Vol. 20, September, 1953, pp. 598-604.

715. Skarecky, R., "The Effect of Torsion in Conductor Galloping", R.D. Rept. No. 69-362-H Hydroelectric Power Commission, Toronto, Canada, 1969.

716. Skarecky, R., "Yaw Effects in the Flow Over a Bluff Cylinder and Their Contribution to Aeroelastic Excitation", Res. Rept., Univ. of Waterloo, Canada, 1972.

717. Skop, R.A., and Griffin, O.M., "A Model for the Vortex Excited Resonant Response of Bluff Cylinders", J. Sound Vib., 27, 1973, pp. 225-233.

718. Skop, R.A., and Griffin, O.M., "On a Theory for the Vortex-Excited Oscillations of Flexible Cylindrical Structures", J. Sound Vib., 1974.

719. Slater, J.E., "Aeroelastic Instability of a Structural Angle Section", Ph.D. Thesis, Univ. of British Columbia, 1969.

720. Slater, J.E., and Modi, V.J., "On the Wind Induced Vibration of Structural Angle Sections", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, IV, 53, September, 1971, 11pp.

721. Smagorinsky, J., "General Circulation Experiments with the Primitive Equations", Monthly Weather Review, Vol. 91, No. 3, 1963, pp. 99-164.

722. Smeaton, J., "An Experimental Investigation Concerning the Natural Powers of Water and Wind", Phil. Trans. Roy. Soc. of London, Vol. 51, 1759-1760, pp. 100-174.

723. Smirno, L.P., Pavlihina, M.A., "Vortical Traces for Flow around Vibrating Cylinders", Presented at the I.M.A. Communications Meeting, Moscow, October, 1957.

724. Smith, A., "Windloads on Buildings", Journal of the Western Society of Engineers, 1912, 1914.

725. Smith, A., and Clutter, D.W., "The Smallest Height of Roughness Capable of Affecting Boundary-Layer Transition in Low-Speed Flow", J. Aerospace Sci., Vol. 26, 1959, pp. 229.

726. Smith, I.P., "The Aeroelastic Stability of the Severn Suspension Bridge", N.P.L., Aero Report 1105, 1964.

727. Smith, I.P., "The Response of Flexible Structures to Atmospheric Turbulence", NPL/Aero/1122, December, 1964.

728. Smith, J.D., "An Experimental Study of the Aeroelastic Instability of Rectangular Cylinders", Thesis, University of British Columbia, 1962.

729. Smith, J.O., and McCarthy, J.H., "Wind Versus Tall Stacks", Mechanical Engineering, January, 1965.

730. Soler, A.I., "On the Dynamics of Cables and Cable System", Sound and Vibration Digest, Vol. 5, No. 3, March, 1973, pp. 2-10.

731. Son, J.S., and Hanratty, T.J., "Numerical Solution for the Flow around a Cylinder at Reynolds Numbers of 40, 200, and 500", J. Fluid Mech., Vol. 35, Part 2, 1969, pp. 369-386.

732. Son, J.S., and Hanratty, T.J., "Velocity Gradients at the Wall for Flow around a Cylinder at Reynolds Numbers from 5×10^3 to 10^5", J. Fluid Mech., Vol. 35, Part 2, 1969, pp. 353-368.

733. Sourochnikoff, B., "Wind Stresses in Semi-Rigid Connections of Steel Framework", Transactions, ASCE, Vol. 115, 1950, pp. 382.

734. Spivack, H.M., "Vortex Frequency and Flow Pattern in the Wake of Two Parallel Cylinders at Varied Spacing Normal to an Air Stream", J. of the Aero. Sc., June, 1946.

735. Standen, N.M., "A Spire Array or Generating Thick Turbulent Shear Layers for Natural Wind Simulation in Wind Tunnels", Tech. Rept. ITR-LA-94, National Aeronautical Establishment, Ottawa, Canada, May, 1972.

736. Standen, N.M., Dalgliesh, W.A., and Templin, R.J., "A Wind Tunnel and Full-Scale Study of Turbulent Wind Pressures on a Tall Building", Proceedings of the Third International Conference on Wind Effects on Buildings and Structures, Tokyo, Japan, September, 1971, pp. 199-209.

737. Stanton, T.E., "Report on Measurement of the Pressure of the Wind on Structures", Proc. Inst. of Civil Engr., Vol. 219, 1924-1925, pp. 125-158.

738. Steinman, D.B., "Rigidity and Aerodynamic Stability of Suspension Bridges", Transactions ASCE, Vol. 110, 1945, pp. 439.

739. Steinman, D.B., "Problems of Aerodynamic and Hydrodynamic Stability", Bulletin 31, Univ. of Iowa Studies in Engrg., Iowa City, Iowa, 1947.

740. Steinman, D.B., "Aerodynamic Theory of Bridge Oscillations", Transactions, ASCE, Vol. 115, 1950, pp. 1180.

741. Stoker, J.J., Nonlinear Vibrations, Interscience, New York, 1957.

742. Strasberg, M., and Cooper, R.D., "Measurements of the Fluctuating Pressure and Velocity in the Wake behind a Cylinder", Proc. 9th Internatl. Congress of Appl. Mech., Brussels, Vol. 2, 1957, pp. 384.

743. Strom, G.H., "Wind Tunnel Techniques Used to Study Influence of Building Configuration on Stack Gas Dispersal", Amer. Indust. Hygiene Assoc. Quarterly, Vol. 13, 1952, pp. 76.

744. Strouhal,V., "Uber eine besonders Art der Tonnerregung", Wied. Ann. Physid. Chem. Neue Floge, Band V. 1878.

745. Strouhal, V., Annalen der Physik und Chemie, Vol. 5, 1878, pp. 216-251.

746. Stuper, J., "The Effect of Surface Excrescencies on the Transition of the Boundary Layer over a Flat Plate", Zeit Flugwissen, Vol.4, 1956, pp. 30.

747. Surry, D., "The Effect of High Intensity Turbulence on the Aerodynamics of a Rigid Circular Cylinder at Subcritical Reynolds Number", University of Toronto Institute for Aerospace Studies, UTIAS Report No. 142, 1969.

748. Suzuki, N., Sato, H., Iuchi, M., and Yamamoto, S., "Aerodynamic Forces Acting on Circular Cylinders Arranged in a Longitudinal Row", Proc. 3rd Internatl. Conf. on Wind Effects on Buildings and Structures, Tokyo, II, 20, September, 1971, 10pp.

749. Swanson, W.M., "The Magnus Effect: A Summary of Investigations to Date", Journal of Basic Engineering, Trans. ASME, Series D, Vol. 83, 1961, pp. 461.

750. Sylvester, H., "Wind Pressure Distribution on Sharp-Edged Bodies", Bygningsstatiske Meddelelser, Vol. 8, 1936, pp. 41.

751. Tack, J., Tests in the Variable-Density Tunnel to Investigate the Effects of Scale and Turbulence on Airfoil Characteristics, NACA Tech. Note No. 364, 1930.

752. Tanaka, H., "Vibrations of Bluff Sectional Structures Under Wind Action", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, IV, 25, September, 1971, 12pp.

753. Tanaka, H., and Davenport, A.G., "The Aerodynamic Stability of the Golden Gate Bridge: Comparison of the Full-Scale Motion with a Taut Strip Wind Tunnel Model", Paper presented at Symposium on Full-Scale Measurements of Wind Effect on Tall Buildings and Other Structures, the University of Western Ontario, London, Ontario, 1974, 24pp.

754. Tanaka, H., and Takahara, S., "Unsteady Air Forces Acting on a Vibrating Circular Cylinder", Proc. 19th Japan National Congress App. Mech., 1969 .

755. Taneda, S., "Oscillation of the Wake Behind a Flat Plate Parallel to the Flow", J. Phys. Soc. Japan, Vol. 13, 1958, pp. 418.

756. Taneda, S., "Studies on Wake Vortices (II) Experimental Investigation of the Wake Behind Cylinders and Places at Low Reynolds Number", Reports of Research Institute for Applied Mechanics, Kyushu University, Vol. 1, 1952, pp. 29-40.

757. Taneda, S., "The Stability of Two-Dimensional Laminar Wakes of Low Reynolds Numbers", J. Phys. Soc. Japan, Vol. 18, 1963, pp. 288.

758. Tani, I., "Low-Speed Flows Involving Bubble Separations", Progress in Aero. Sci., Vol. 5, 1964, pp. 70-103.

759. Tani, I., "Some Aspects of Boundary Layer Transition at Subsonic Speeds", Advances in Aero. Sci., Vol. 3, Pergamon Press, 1962, pp. 121.

760. Tani, I., "Note on Interplay between the Laminar Separation and the Transition from Laminar to Turbulent of the Boundary Layer", J. Soc. Aero. Sci., Japan, Vol. 6, 1939, pp. 122.

761. Tani, I., "Critical Survey of Published Theories on the Mechanism of Leading-Edge Stall", Aero. Res. Inst., Univ. of Tokyo, Rept. No. 367, 1961.

762. Tani, I., "Effect of Two-Dimensional and Isolated Roughness on Laminar Flow", Boundary Layer and Flow Control, G.V. Lachman, (ed), Pergamon Press, Vol. 2, 1961, pp. 637-656.

763. Tani, I., and Komoda, H., "Boundary-Layer Transition in the Presence of Streamwise Vortices", J. Aerosp. Sci., Vol. 29, 1962, pp. 440.

764. Tani, I., Komoda, H., Komatsu, Y., and Iuchi, M., "Boundary-Layer Transition by Isolated Roughness", Aero. Res. Inst. Tokyo Rept. No. 375, November, 1962.

765. Tanida, Y., Okajima, A., and Watanabe, Y., "Stability of a Circular Cylinder Oscillating in a Uniform Flow or in a Wake", J. Fluid Mech., Vol. 61, 1973, pp. 769-784.

766. Taylor, Sir G.I., "The Statistical Theory of Turbulence", Parts I-IV, Proc. Roy. Soc. of London, Vol. A 151, 1945, pp. 421.

767. Teunissen, H.W., "Simulation of the Planetary Boundary Layer in a Multiple-Jet Wind Tunnel", Institute of Aerospace Studies, Rept. 182, University of Toronto, Toronto, Canada, 1972, 162pp.

768. Theodorsen T., "Gerneral Theory of Aerodynamic Instability and the Mechanism of Flutter", NACA Report 496, 1935.

769. Thom, A., "The Flows Past Circular Cylinders at Low Speeds", Proc. Roy. Soc., London, Series A, Vol. 141, 1933, pp. 651-669.

770. Thom, H.C.S., "New Distributions of Extreme Winds in the United States", J. Struct. Div. ASCE, Vol. 94, July, 1968, pp. 1781-1801.

771. Thom, A., "The Laminar Boudary Layer of the Front Part of a Cylinder", ARC Rept. and Memo. 1176, 1928, and Rept. 1194, 1929.

772. Thom, H.C.S., "Distribution of Extreme Winds in the United States", Proceedings, ASCE, Vol. 86, No. ST4, April, 1960.

773. Thomann, H., "Measurement of the Recovery Temperature in the Wake of a Cylinder and of a Wedge at Mach Numbers between 0.5 and 3", FFA (Aero Res. Inst. of Sweden), Rept. No. 84, 1959.

774. Thompson, R.A., "Protection of Small Buildings Against High Velocity Winds", Bull. 28, Fla. Engrg. and Industrial Experiment Sta., Gainesville, Fla., 1949.

775. Thomson, W.T., Vibration Theory and Applications, Prentice-Hall, Englewood Cliffs, N.J., 1965.

776. Thompson, W.T., and Barton, M.V., "The Response of Mechanical Systems to Random Excitation", J. of Appl. Mechanics, Vol. 24, 1957, pp. 248-251.

777. Tietjens, O.G., Applied Hydro-and Aero-Mechanics, Dover, 1957, pp. 286.

778. Timman, R., Zaat, J.A., and Burgerhout, T.J., "Stabil-Diagrams for Laminar Boundary Layer Flow", Nat. Aero. Inst. of Holland, Tech. Note, F193, 1956.

779. Timme, A., "Uber die Geschwindigkeitsverteilung in Wirbelin" Ing. Archiv., Vol. 25, 1957, pp. 205-225.

780. Timoshenko, S., Vibration Problems in Engineering, Van Nostrand Co., New York, Third Edition, 1955.

781. Toebes, G.H., "Flow-Induced Structural Vibrations", J. Eng. Mech., Proc. ASCE, Vol. 91, (EM6), 1965, pp. 39.

782. Toebes, G.H., "Fluidelastic Features of Flow around Cylinders", Proc. Int. Res. Sem. Wind Effects on Building and Structures", Ottawa, 1967.

783. Toebes, G.H., "The Unsteady Flow and Wake Near an Oscillating Cylinder", Trans. ASME, J. Basic Eng., Vol. 91, 1969, pp. 493-505.

784. Toebes, G.H., and Eagleson, P.S., "Hydroelastic Vibrations of Flat Plates Related to Trailing Edge Geometry", Journal of Basic Engineering, Trans. ASME, Series D., Vol. 83, 1961, pp. 671.

785. Toebes, G.H., and Ramamurthy, A.S., "Fluidelastic Forces on Circular Cylinders", Proc. Am. Soc. Civil Eng. J. Engr. Mech. Div., Vol. 93, No. EM6 Paper 5627, 1967, pp. 1-20.

786. Toebes, G.H., and Ramamurthy, A.S., "Lift and Strouhal Frequency for Bluff Shapes in Constructed Passages", Proc. Conf. Flow-Induced Vib. Reactor Sys. Components, ANL-7685, 1970, pp. 225-247.

787. Takaty, G.A., A History and Philosophy of Fluidmechanics, G.T. Flulis and Co., Ltd, Henly-on-Thames, Oxfordshire, 1971, 24pp.

788. Tompkins, J.S., Merill, L.L., and Jone, B.L., "Quantitative Relationships in Conductor Vibration Damping", Trans. AIEE, Vol. 75, 1956, pp. 879-894.

789. Tornquist, E.L., and Becker, C., "Galloping Conductor and a Method for Studying Them", Trans. AIEE, Vol. 66, 1947, pp. 1154-1161.

790. Tritton, D.J., "Experiments on the Flow Past a Circular Cylinder at Low Reynolds Numbers", J. of Fluid Mech., 1971, pp. 203-208.

791. Tritton, D.J., "A Note on Vortex Streets Behind Circular Cylinders at Low Reynolds Number", J. Fluid Mech., Vol. 45, 1971, pp. 203-208.

792. Troltsky, M.S., and Lazar, B.E., "Model Investigation of Cable Stayed Bridges", Paper Presented at 3rd Canadian Congress of Applied Mechanics, Calgary, Canada, May, 1971.

793. Tsuchiya, K., "The Clouds with the Shape of Kármán Vortex Street in the Wake of Cheja Island, Korea", J. Meteorol. Soc. Japan, Vol. 47, No. 6, 1969, pp. 457-465.

794. Turner, D.B., "Workbook of Atmospheric Dispersion Estimates", Public Health Service Publication No. 999-AP-26, National Air Pollution Control Administration, Cincinnati, Ohio, 1969, 84pp.

795. Turner, J.J., Warters, R.L., and Eagleson, P.S., "The Effect of Transverse Body Vibration on the Spanwise Correlation of Instantaneous Structure for Flat Plates", Hydrodynamics Laboratory Report 81, M.I.T., 1965.

796. Twigge-Molecey, C.R.M., and Baines, W.D., "Measurements of Unsteady Pressure Distributions Due to Vortex Induced Vibration of a Cylinder of Triangular Section", IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper E1, August, 1972.

797. Tyler, E., "Vortex Formation behind Obstacles of Various Sections", Philosophical Magazine, Vol. 11, 1931, pp. 849-890.

798. Uber die Tragheitsfehler des Schalenkreuz-Anemometers bei Schwankender Windstarke, Z. Tech. Phys., Berlin, 10, 57, 1929.

799. Ujihara, B.H., "Hydroelastic Analysis of a Circular Cylinder", North American Rockwell Space Division Rep. SD68-996, 1968.

800. Ukeguchi, M., Sakata, H., and Nishitani, H., "An Investigation of Aero-Elastic Instability of Suspension Bridges", Proc. Symposium on Suspension Bridges, Lisbon, Portugal, November, 1966.

801. Umemura, S., Uamaguchi, T., and Shiraki, K., "On the Vibration of Cylinders Caused by Kármán Vortex", Bull. Jap. Soc. Mech. Engrs., Vol. 14, Part 75, 1971, pp. 929.

802. Underwood, R.L., "Calculation of Incompressible Flow Past a Circular Cylinder at Moderate Reynolds Numbers", Journal of Fluid Mechanics, Vol. 37, 1969, pp. 95-114.

803. Unger, E.E., "Damping of Panels", Noise and Vibration Control, McGraw-Hill, New York, 1971.

804. Valensi, J., and Flinois, A., "Establissement D'un mur Pare-Vent Perfore pour les Navires a Qui", Association Technique Martime et Aeronautique, Session 1955, 21pp.

805. Valensi, J., and Rebont, J., "Aerodynamics of Perforated Walls: Application to the Wind-Protection Screen Project: Study of the Functioning of Such Screens", Paper Presented at the AGARD Fluid Dynamics Panel Specialists Meeting, Munich, Paper 27, 1970.

806. Varney, T., "Vaibration in Overhead Conductors", J. IEE, Vol. 77, 1935, pp. 407-419.

807. Vellozzi, J., and Cohen, E., "Dynamic Response of Tall Flexible Structures to Wind Loading", Wind Loads on Buildings and Structures, Nat. Bureau of Stand. Build. Sci. Series 30, 1970, pp. 115-128.

808. Vellozzi, J., and Cohen, E., "Gust Response Factors", J. Struct. Div., ASCE, Vol. 94, ST6, June, 1968.

809. Vickery, B.J., "Fluctuating Lift and Drag on a Long Cylinder of Square Cross Section in a Smooth and in a Turbulent Stream", Journal of Fluid Mechanics, Vol. 25, Part 3, 1966, pp. 481-494.

810. Vickery, B.J., "On the Flow Behind a Coarse Grid...", NPL/ Aero/1143, March, 1965.

811. Vickery, B.M., "On the Reliability of Gust Loading Factors", U.S. Nat'l Bureau of Stds, Bldg. Sci., Series 30, 1970.

812. Vickery, B.J., and Kao, K.H., "Drag or Along-Wind Response of Slender Structures", J. Struct. Div. ASCE, ST1, January, 1972, pp. 21-36.

813. Vickery, B.J., and Watkins, R.D., "Flow-Induced Vibration of Cylindrical Structures", Proc. of the First Australian Conference, University of Western Australia, 1962.

814. Vincent, G.S., "Investigation of Wind Forces on Highway Bridges", Highway Research Board Special Report 10, No. 272, 1953.

815. Vincent, G.S., Aerodynamic Stability of Suspension Bridges, Pt. V, Univ. of Washington, Bull. No. 116, 1954.

816. Vincent, G. S., "Summary of Laboratory and Field Studies in the U.S.A. on Wind Effects on Suspenstion Bridges", NPL Symposium, Paper 20, H.M.S.O., 1965.

817. Vincent, G.S., "A Summary of Laboratory and Field Studies in the United States on Wind Effects on Suspension Bridges", Effects on Buildings and Structures, Teddington, England 26-28, June, 1963.

818. von Doenhoff, A.E., and Braslow, A.L., "The Effect of Distributed Surface Roughness on Laminar Flow", Boundary Layer and Flow Control, G.V. Lachman, (ed), Pergamon Press, Vol. 2, 1961, pp. 657-681.

819. Votow, C.W., and Griffin, O.M., "Vortex Shedding from Smooth Cylinders and Stranded Cables", Journal of Basic Engineering, September, 1971.

820. Waller, R.A., "Design Techniques for Practical Wind Problems", Dynamic Waves in Civil Engineering, Howells, D.A., Haigh, I.P., and Taylor, C., (ed), Wiley-Interscience, 1971.

821. Walshe, D.E., "The Use of Perforated Shrouds for Suppressing Vortex Excitation of Cylinders of Square Section", Nat. Phys. Lab., NPL Mar. Sci. Tech. Memo 2-71, October, 1971, 8pp.

822. Walshe, D.E.J., "Wind-Excited Oscillations of Structures", National Physcial Laboratory, Teddington, England, H.M.S.O., 49 High Holborn, London WCIV6HB.

823. Walshe, D.E.J., "Use of Models to Predict the Oscillatory Behaviour of Suspension Bridges in Wind ", NPL Symposium, Paper 17, H.M.S.O., 1962.

824. Walshe, D.E.J., "Aerodynamic Stability Measurements on a Model of a Section of the Jonsknuten Transmitting Tower", NPL/Aero/1080, 1963.

825. Walshe, D.I.J., "Aerodynamic Investigation for the Proposed 850' High Chimney Stack for the Drax Power Station", NPL/Aero/1227, 1967.

826. Walshe, D.E., and Wootton,L.R.,"Preventing Wind-Induced Oscillations of Structures", Proc. Inst. Civ. Engrs., Vol. 47, 1970, pp. 1-24.

827. Walshe, D.E., and Packer, M.A., "Investigation of the Aerodynamic Stability of the fourth Suspension Bridge at Various Stages of Construction", NPL/Aero/1052, 1963.

828. Walton, C.O., and Merriam, M.M., "Vibration and Towing Characteristics of Surface-Suspended Hydrophone Systems", DTMB Report 1558, August, 1961.

829. Walton, E.T.S., "The Formation of Vortex behind a Cylinder Moving through a Fluid", Scientific Proc. of the Royal Dublin Society, Vol. 18, 0.47, 1928, pp. 521-534.

830. Ward, H.S., and Rainer, J.H., "Experimental Determination of Structure and Foundation Parameters Using Wind-Induced Vibrations", Proc. Inst. of Civil Engrs., 53, Part 2, September, 1972, pp. 305-321.

831. Ward, N.B., "The Exploration of Certain Features of Tornado Dynamics Using a Laboratory Model", Journal of the Atmospheric Sciences, Vol. 29, No. 6, 1972, pp. 1194-1204.

832. Wardlaw, R.L., "Damped Vibration Absorbers for Suppressing Wind Induced Vibrations of Structures", Proc. 3rd Canadian Congress on Applied Mechanics, pp. 481-482, May, 1971.

833. Wardlaw, R.L., "Some Approaches for Improving the Aerodyamic Stability of Bridge Road Decks", Proc. 3rd International Conf. on Wind Effects on Buildings and Structures, Tokyo, IV, 28, September, 1971, 10pp.

834. Warschauer, K.A., and Leene, J.A., "Experiments on Mean and Fluctuating Pressures of Circular Cylinders at Cross Flow at Very High Reynolds Numbers", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, II, 13, September, 1971, 11pp.

835. Waters, J.F., "Cable Towing Critical Angle as a Function of Array Weight/Drag Ratio", Tech. Memorandum, HRC, May, 1972.

836. Weaver, W., "Wind-Induced Vibrations in Antenna Members", Journal of Engr. Mech., ASCE, Vol. 87, No. EM1, 1961, pp. 141-165.

837. Weaver, W., "Experimental Investigation of Wind-Induced Vibration in Antenna Members", Group Report No. 75-4, Lincoln Lab., Mass, Inst. of Tech. Cambridge, Mass., August, 1959.

838. Wehner, H., "Untersuchung Mikrobarographischer Wellen auf Jan Mayen", Dissertation Univ. Leipzig, Berlin: Akademie-Verlag, 1949.

839. Welsh, R.I., "The Effectiveness of a Splitter Plate in Reducing Transverse Oscillations of a Finite Circular Cylinder in Turbulent Flow", NUSL, New London, USL Report No. 759, September, 1966.

840. Whitbread, R.E., "Practical Solutions to Some Wind-Induced Vibration Problems", Proc. International Symp. on Vibration Problems in Industry, Teddington, Paper No. 126, April, 1973, 20pp.

841. Whitbread, R.E., "Aerodynamic Investigation of a Model of a Proposed 1000ft. Reinforced Concrete Television Tower", NPL/Aero/1080, 1963.

842. Whitbread, R.E., "Model Simulation of Wind Effects on Structures", N.P.L Symposium No. 16, H.M.S.O., 1965.

843. Whitbread, R.E., Aerodynamic Excitation of Structures by Wind, A Review of Recent Work at the NPL, NASA Langley Res. Center, June, 1966.

844. Whitbread, R.E., and Scruton, C., "An Investigation of the Aerodynamic Stability of a Model of the Proposed Tower Blocks for the World Trade Center, New York", National Physical Laboratory, Aero. Rept. 1156, 40pp.

845. Whitbread, R.E., and Packer, M.A., "Pressure Distribution on a Hyperbolic Paraboloid Roof", NPL/Aero/1077, 1962.

846. Whitbread, R.E., Scruton, C., and Charlton, T.M., "Aerodynamic Investigation of the 437' Tower Block Proposed for the Albert Embankment", Vauxhall, London, NPL/Aero/1032, 1962.

847. Whittingham, H.E., "Extreme Wind Gusts in Australia", Austral. Bur. Met., Bull., 46, 1964.

848. Wieselsberger, C., "Neuere Feststellungen uber die Gesetze des Flussigkeits-und Luftwiderstands", Phys. Z., Vol. 22, pp. 321-328.

849. Wieselsberger, C., "Ergebnisse Aerodynamische Versichanstalt Gottingen", L. Prandtl, ed., Vol. 2, 1923, pp. 23.

850. Wilkinson, R.H., Chaplin, J.R., and Shaw, T.L., "On the Corrlation of Dynamic Pressures on the Surface of a Prismatic Bluff Body", IUTAM/IAHR Symp. on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper E4, August, 1972.

851. Wille, R.,"Generation of Oscillatory Flows", Proc. IUTAM/IAHR Symp. on Flow-Induced Structural Vibrations, Karlsruhe, August, 1972, 12pp.

852. Wille, R., "Karman Vortex Streets", Advances in Applied Mechanics, Vol. 6, 1960, pp. 273-287.

853. Williams, D.H., Nixon, H.L., and Skelton, W.C., "Experiment on a Static Model of a Section of the Severn Bridge", Natl. Physical Lab., England, Aero/209.

854. Williams, D.H., Nixon, H.L., and Skelton, W.C., "Tests of a Plate Girder Bridges in the Duplex Wind Tunnel", Natl. Physical Lab., England, Aero/216.

855. Willmarth, W.W., "Measurements of the Fluctuating Pressure at the Wall beneath a Thick Turbulent Boundary Layer", J. Fluid Mech., Vol. 14, 1962, pp. 187.

856. Willmarth, W.W., and Enlow, R.L., "Aerodynamic Lift and Moment Fluctuations of a Sphere", J. of Fluid Mechanics, Vol. 36, Part 3, 1969.

857. Wilson, J.F., and Caldwell, H.M., "Force and Stability Measurements on Models of Submerged Pipelines", J. Engr. Ind., Trans. ASME, Vol. 3, 1971, pp. 1290-1298.

858. Winants, V., and Riez, M., "Conductor Galloping on Overhead Lines", CIGRE Paper 22-06, August, 1970, 12pp.

859. "Wind Loads on Structures", Division of Building Research Paper No. 88, Ottowa 1960.

860. Winternitz, F.A.L., "The Effects of Vibration on Pilot Tube Readings", D.S.I.R., Mech. Eng. Research Lab. Unpublished Fluids Report No. 33, 1955.

861. Wise, A.F.E., "Effects Due to Groups of Buildings", Phil. Trans. of the Royal Society of London, Series A., Vol. 269, No. 1199, 1971, pp. 469-485.

862. Wise, A.F.E., Sexton, D.E., and Lillywhite, M.S.T., "Studies of Air Flow Round Buildings", Architects's Journal Information Library, May, 1965.

863. Wissmann, J.W., "Dynamic Stability of Space Vehicles: Structural Dynamics Model Testing", NASA CR-1195, 1968.

864. Wood, C.J., "Discussion of Paper C5,in Opening Addresses, Discussions and Contributions", IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, August, 1972.

865. Wood, C.J., "Visualization of an Incompressible Wake with Base Bleed", J. Fluid Mech., Vol. 29, 1967, pp. 259-275.

866. Woodgate, L., and Mabrey, J.F.M., "Further Experiments on the Use of Helical Strakes for Avoiding Wind Excited Oscillations of Structure with Circular or Near Circular Cross Section", NPL/Aero/381, June, 1959.

867. Wootton, L.R., "The Oscillations of Large Circular Stacks in Wind", Proc. Instn. Civ. Engrs., Vol. 43, August, 1968, pp. 573-598.

868. Woototon, L.R., and Scruton, C., "Aerodynamic Stability", Proc. of Seminar on the Modern Design of Wind Sensitive Structures, The Institution of Civil Engineers, London England, June, 1970, pp. 65-81.

869. Wootton, L.R., Warner, M.H., and Cooper, D.H., "Some Aspects of the Oscillations of Full-Scale Piles", IUTAM/IAHR Symposium on Flow-Induced Structural Vibrations, Karlsruhe, Germany, Paper F1, August, 1972.

870. Wootton, L.R., Warner, M.H., Sainsbury, R.N., and Cooper, D.H., "Oscillations of Piles in Marine Structures", CIRIA Report 40, 1972.

871. Wootton, L.R., "The Oscillations of Model Circular Stacks due to Vortex Shedding at Reynolds Numbers in the Range 10^5 to 3×10^6", Symp. Wind Effects on Buildings and Structures, Loughborough, April, 1968.

872. Wyatt, T.A., "The Calculation of Structural Response", Preprints to CIRIA Seminar on the Modern Design of Wind-Sensitive Structures, June 1970, 8pp.

873. Wyatt, T.A., "Effect of Wind on Slender Long-Span Bridges", Paper 36, Loughborough Conference.

874. Yakovlev, L.V., "Investigation into Conductor Galloping", Elekt. Stantstii, Vol. 7, 1970, pp. 49-51, (in Russian).

875. Yamaguchi, T., Shiraki,K., and Umemura, S., "Vibration Caused by Karman Vortex on Bridge Members and its Countermeasures", Proc. 3rd International Conference on Wind Effects on Buildings and Structures, Tokyo, IV,II, September, 1971, 10pp.

876. Young, J.O., "Effect of Cavitation on Periodic Wakes behind Symmetric Wedges", M.S. Thesis, Pennsylvania State University, March, 1965.

877. Young, D., and Felgar, R.P.,"Tables of Characteristic Functions Representing the Normal Modes of Vibration of a Beam", University of Texas Publication No. 4913, 1949.

878. Zdravkovich, M.M., "Smoke Observations of the Formation of a Karman Vortex Street", J. Fluid Mech., Vol. 37, 1969, pp. 491-499.

PART E (APPENDIX B) COMPLETE SET OF GRAPHS

FOR NATURAL FREQUENCY COEFFICIENTS AT DIFFERENT LEVELS

OF AXIAL TENSION

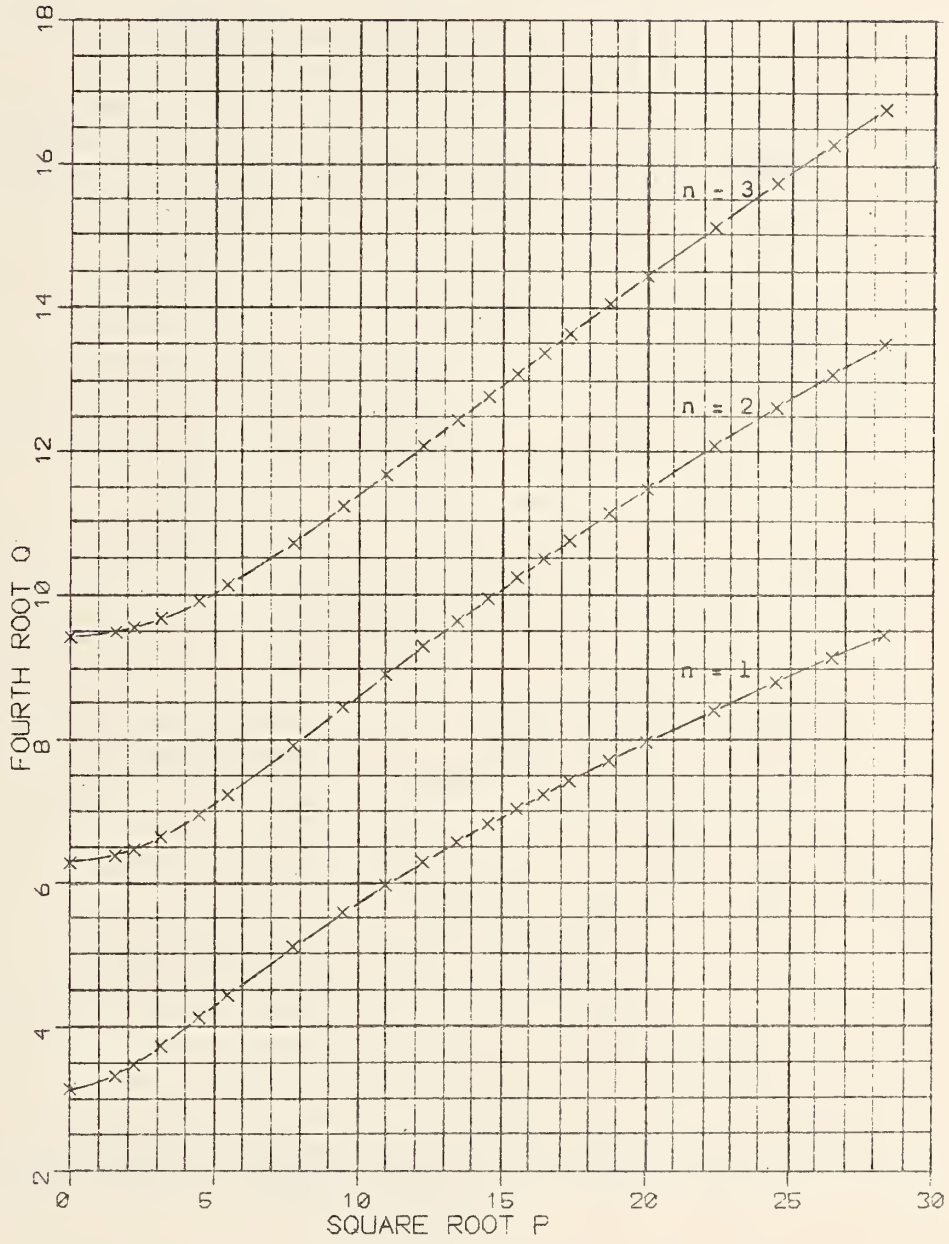
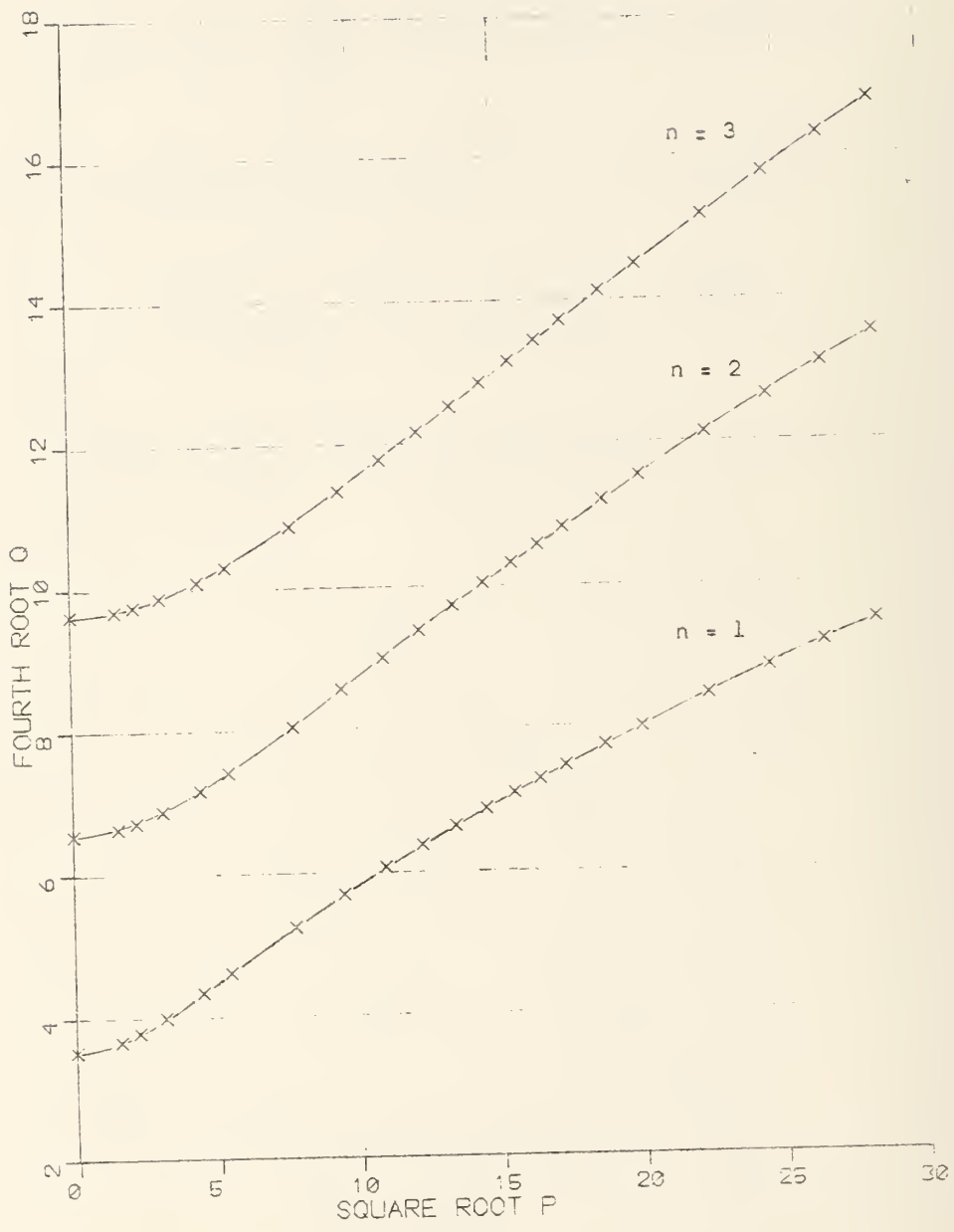


Fig. 36 Both ends hinged



MODE OF VIBRATION = n

Fig. 37 One end hinged, other end $\sigma = 5$

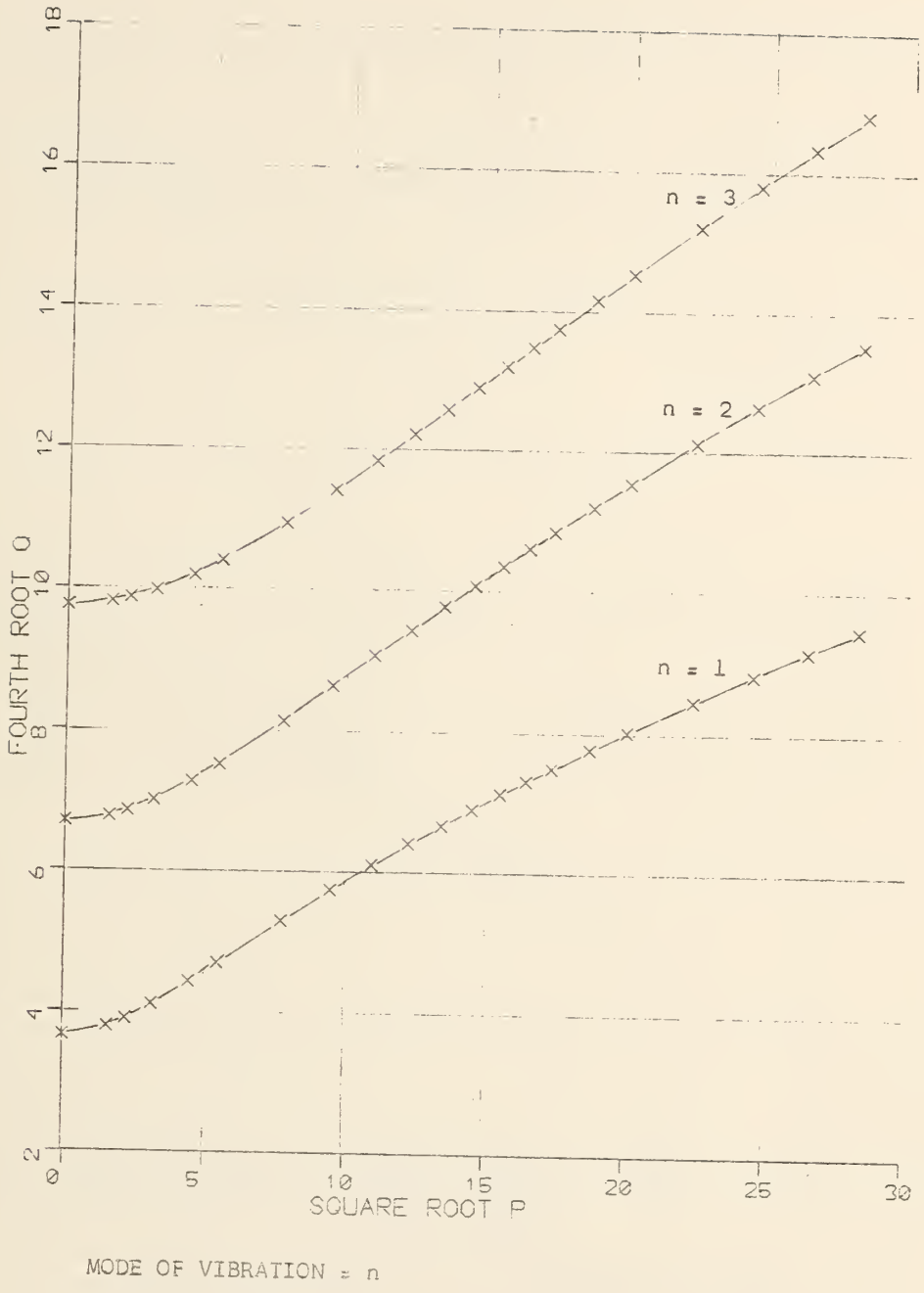
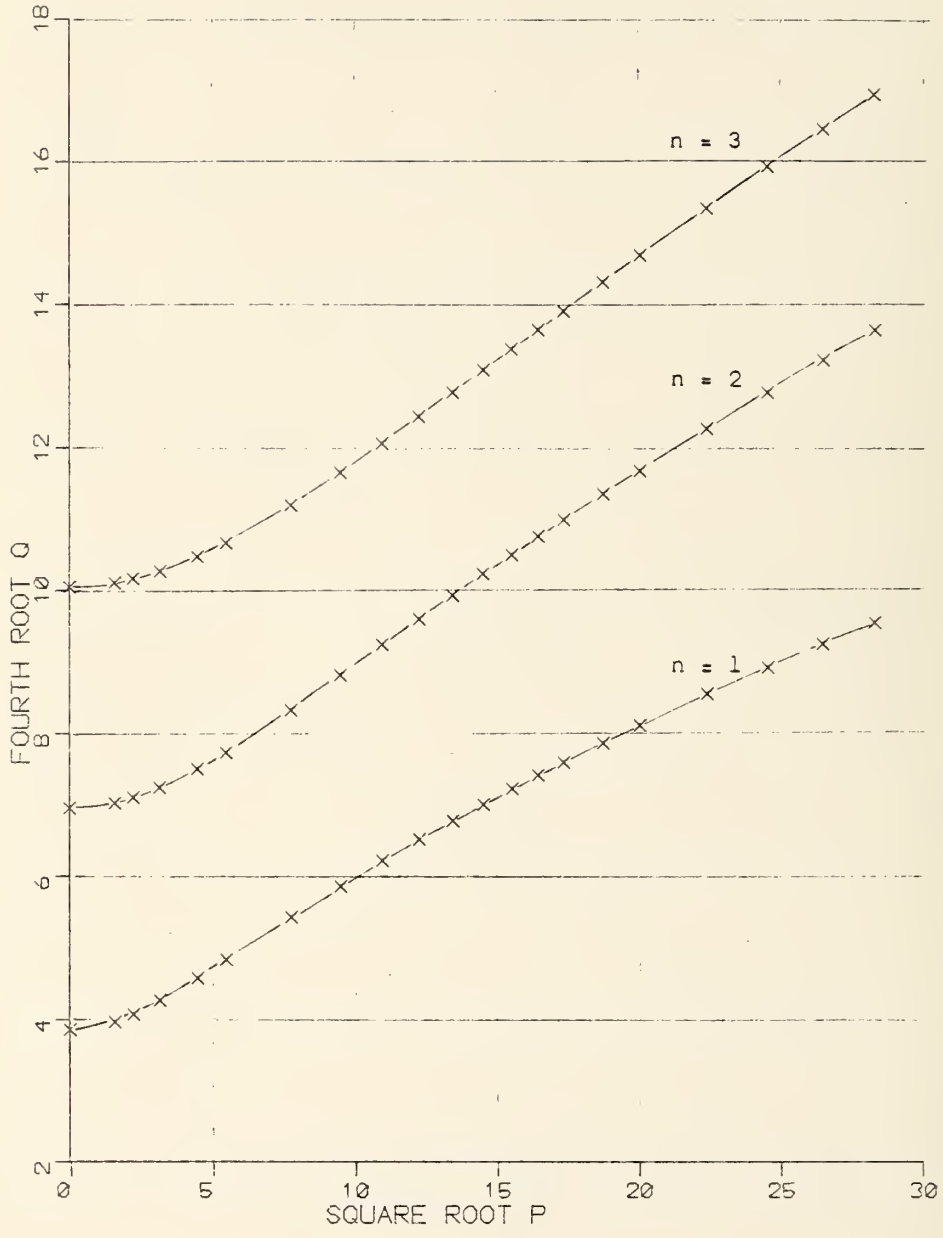
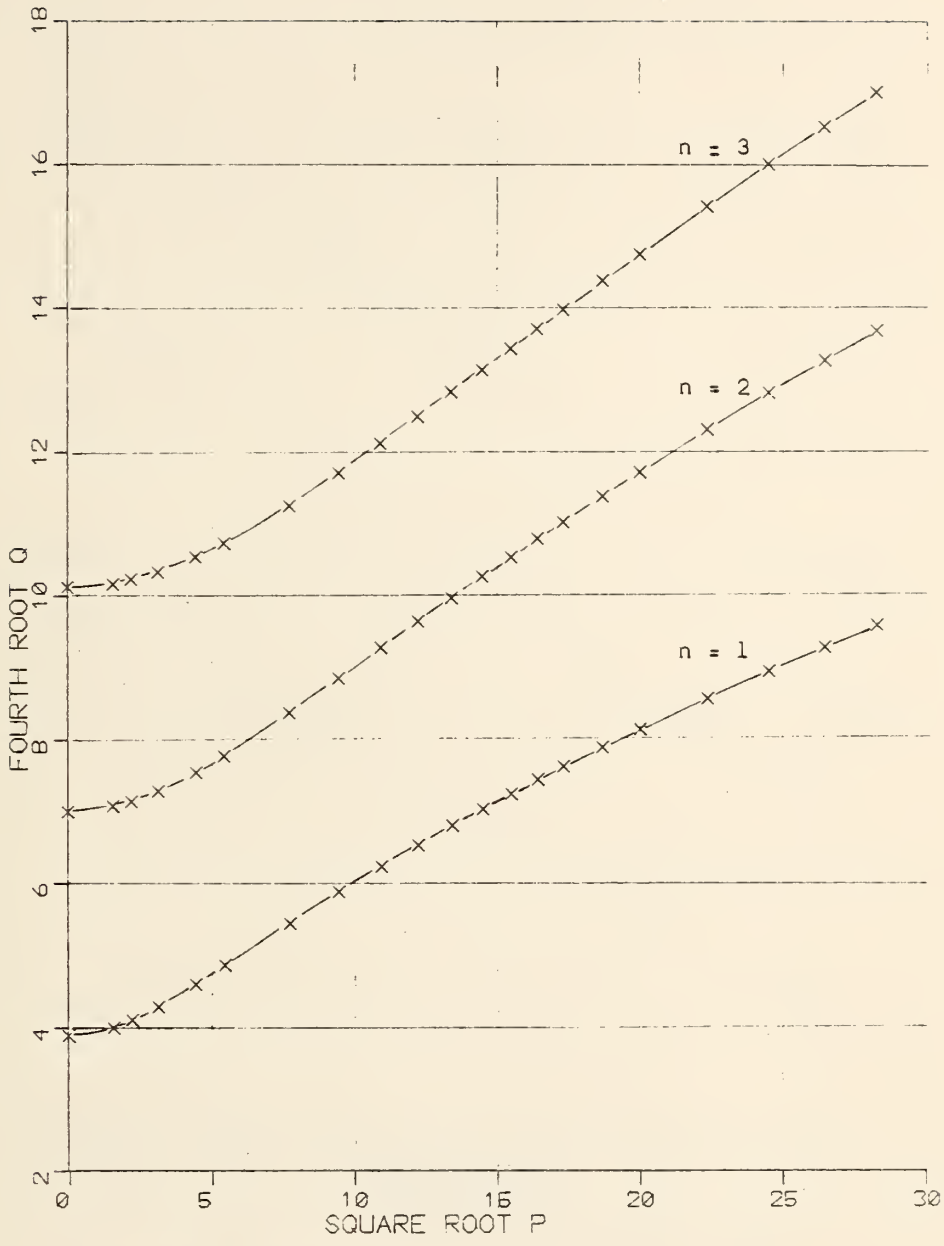


Fig. 38 One end hinged, other end $\sigma = 10$



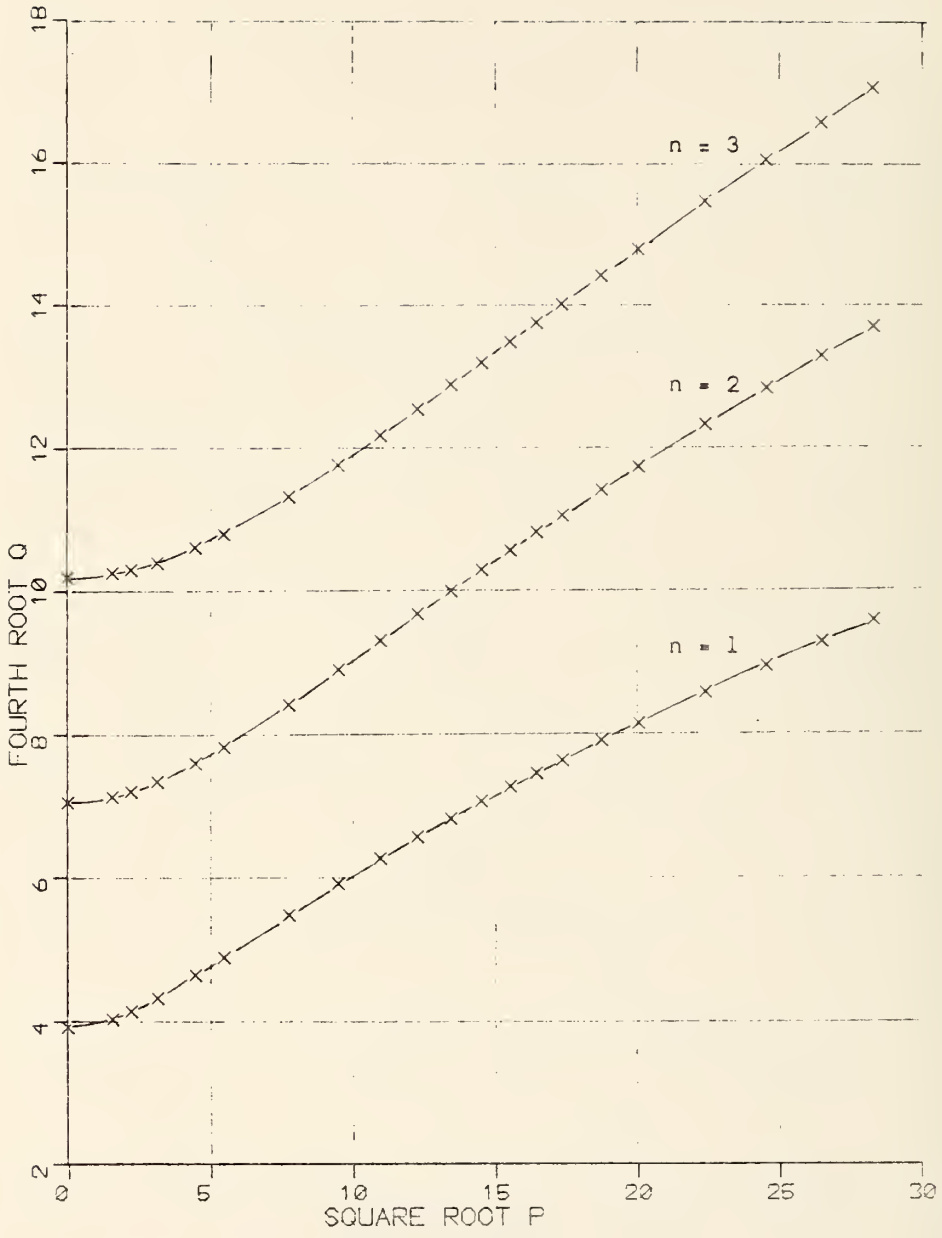
MODE OF VIBRATION = n

Fig. 39 One end hinged, other end $\sigma = 50$



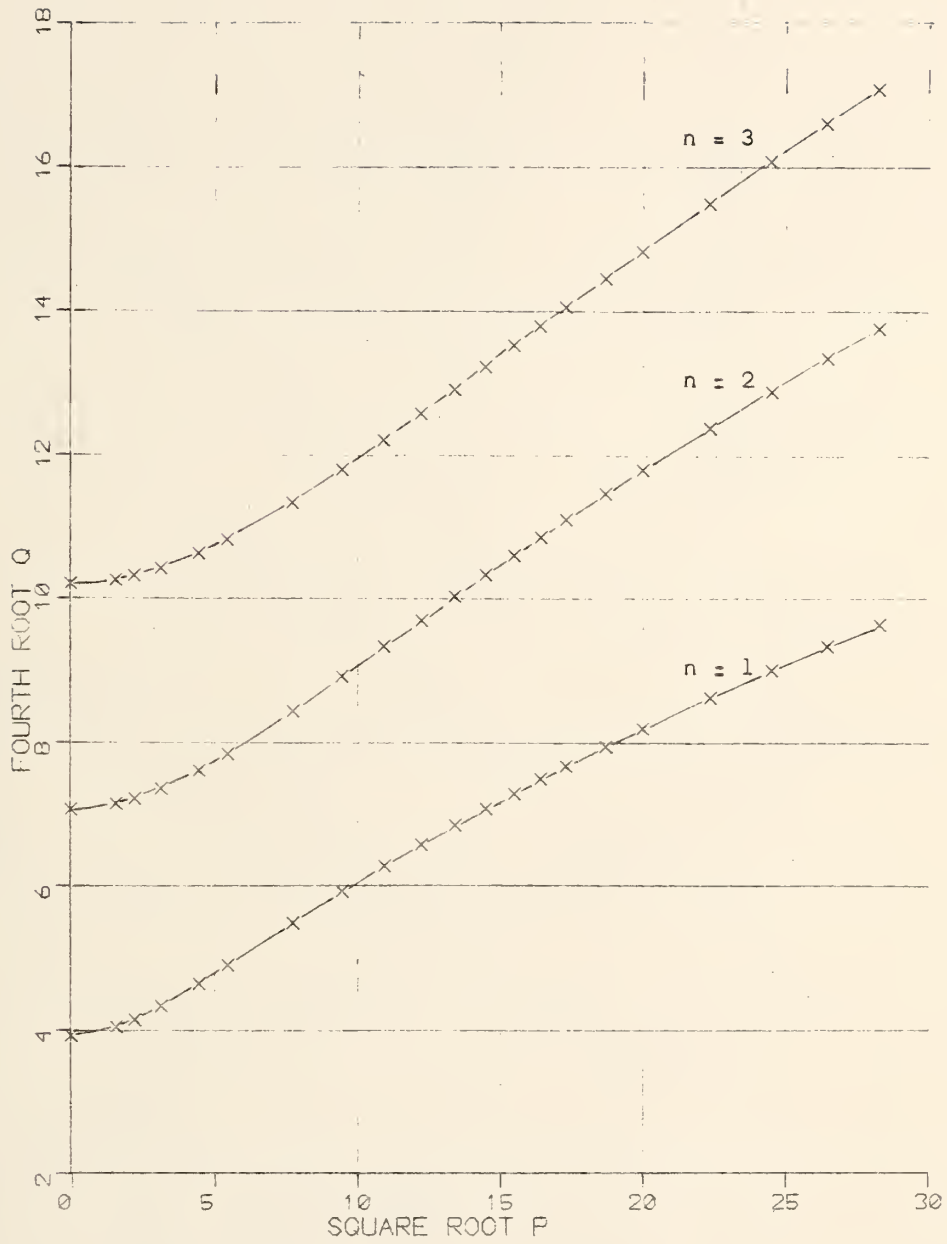
MODE OF VIBRATION = n

Fig. 40 One end hinged, other end $\sigma = 100$



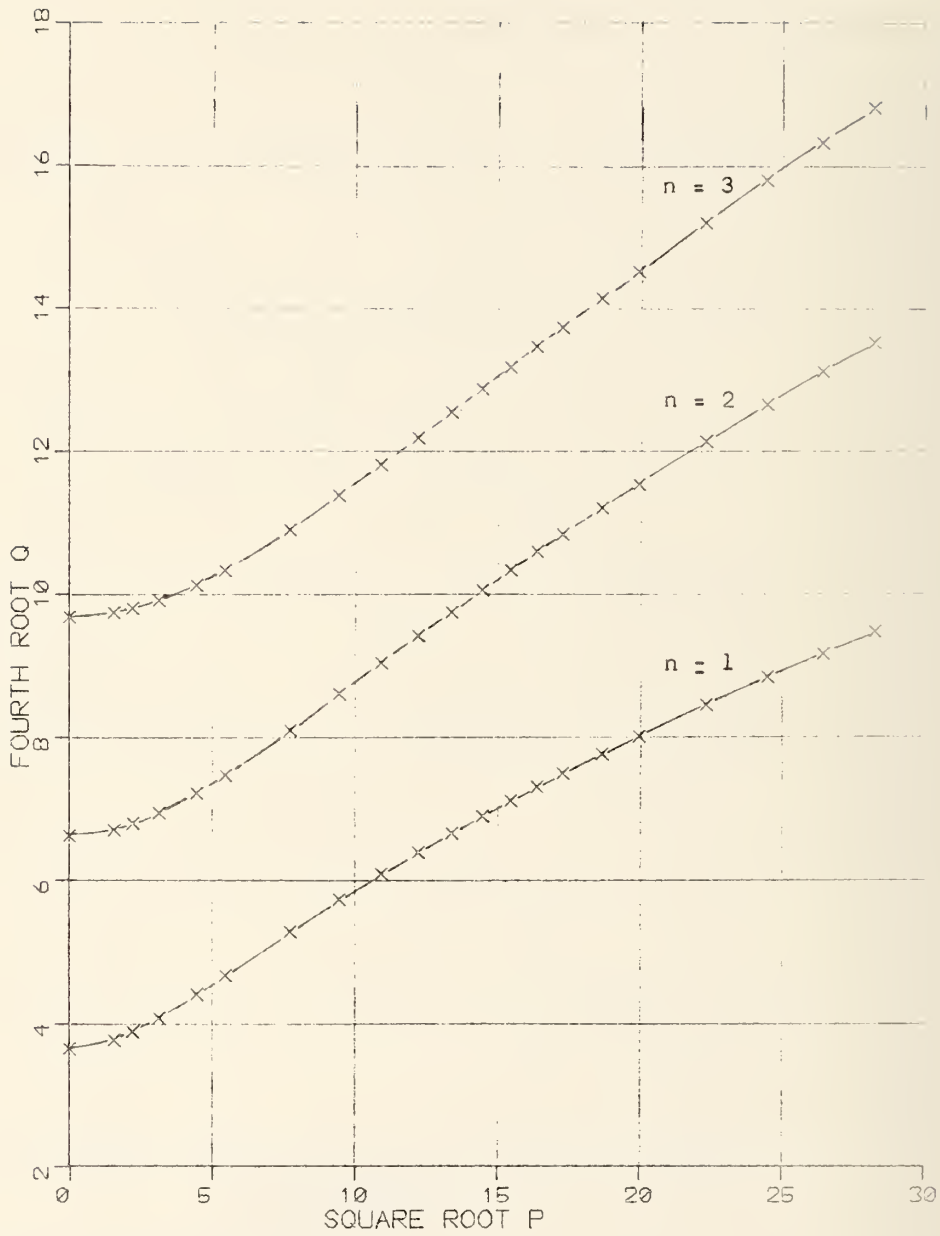
MODE OF VIBRATION = n

Fig. 41 One end hinged, other end $\sigma = 500$



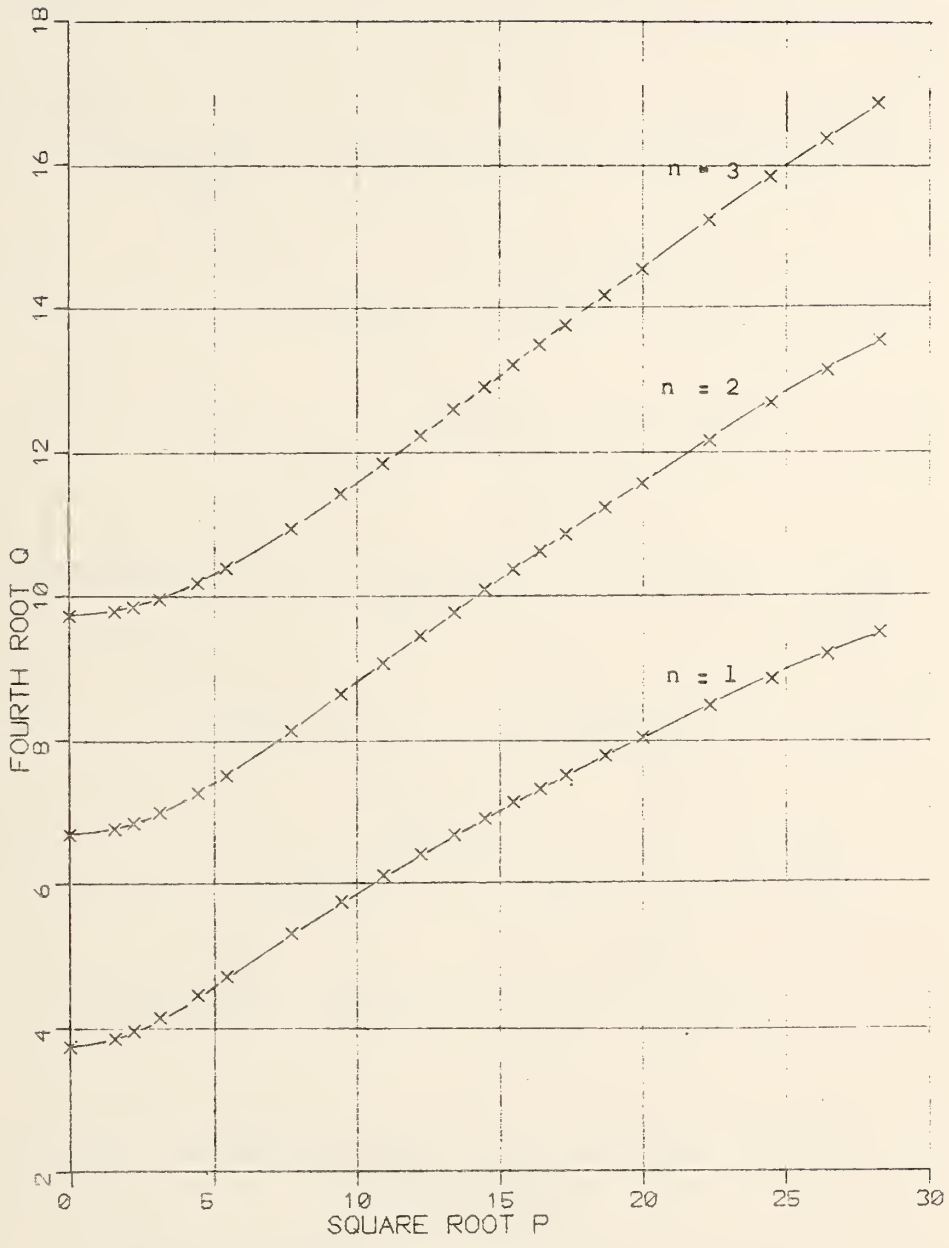
MODE OF VIBRATION = n

Fig. 42 One end hinged, other end $\sigma = 1000$



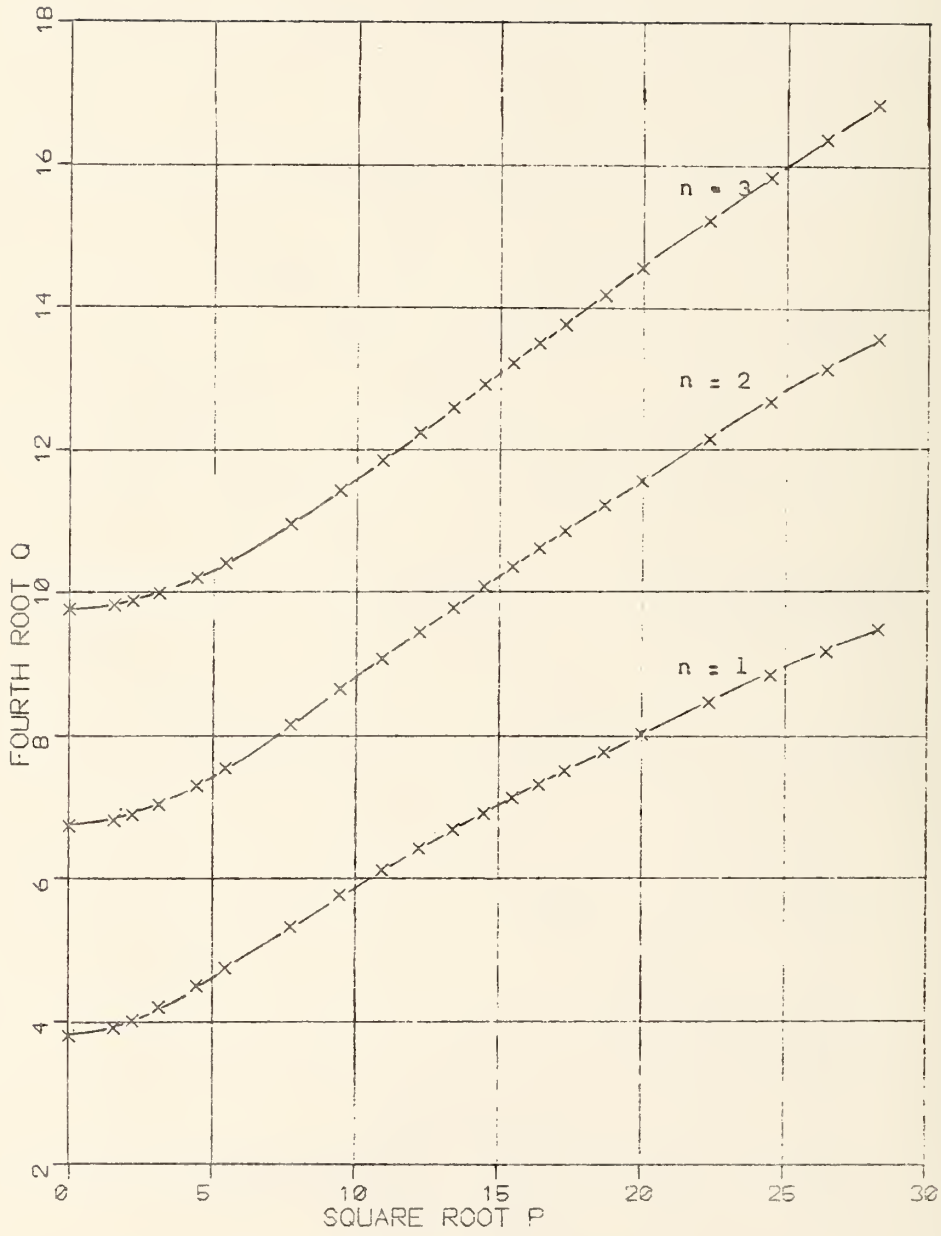
MODE OF VIBRATION = n

Fig. 43 $\sigma_1=5$, $\sigma_2=1$



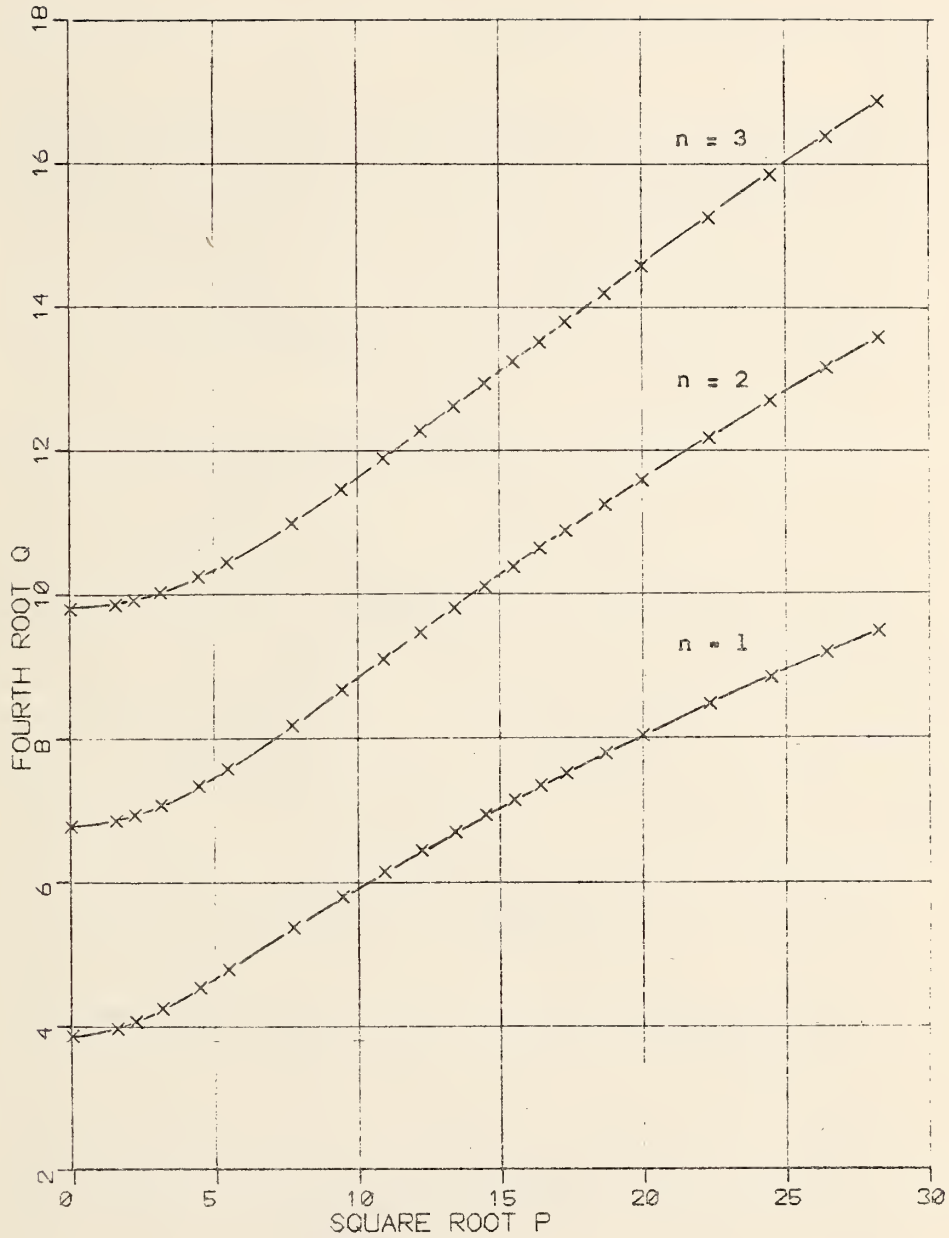
MODE OF VIBRATION = n

Fig. 44 $\sigma_1=5$, $\sigma_2=2$



MODE OF VIBRATION = n

Fig. 45 $\sigma_1 = 5$, $\sigma_2 = 3$



MODE OF VIBRATION = n

Fig. 46 $\sigma_1=5$, $\sigma_2=4$

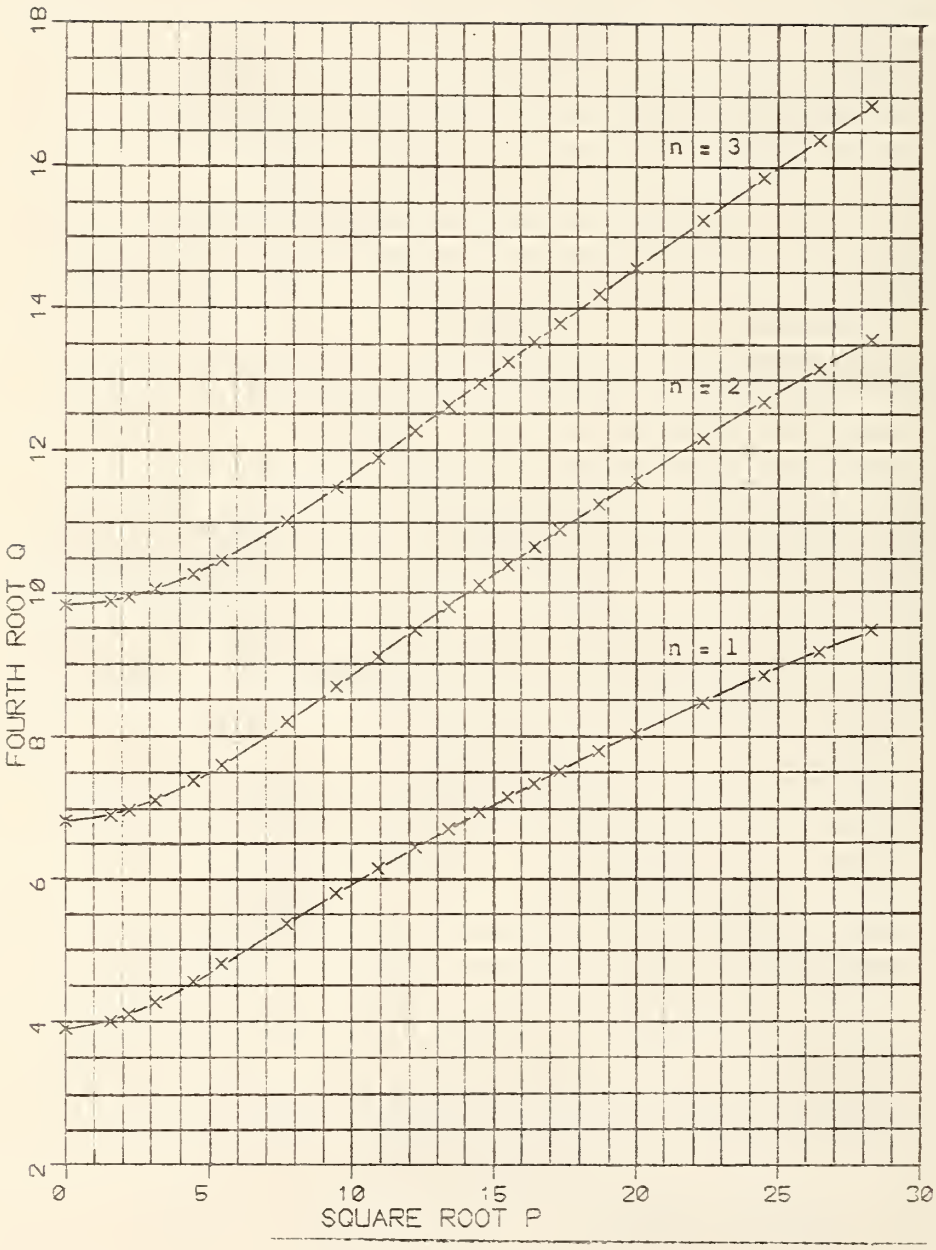
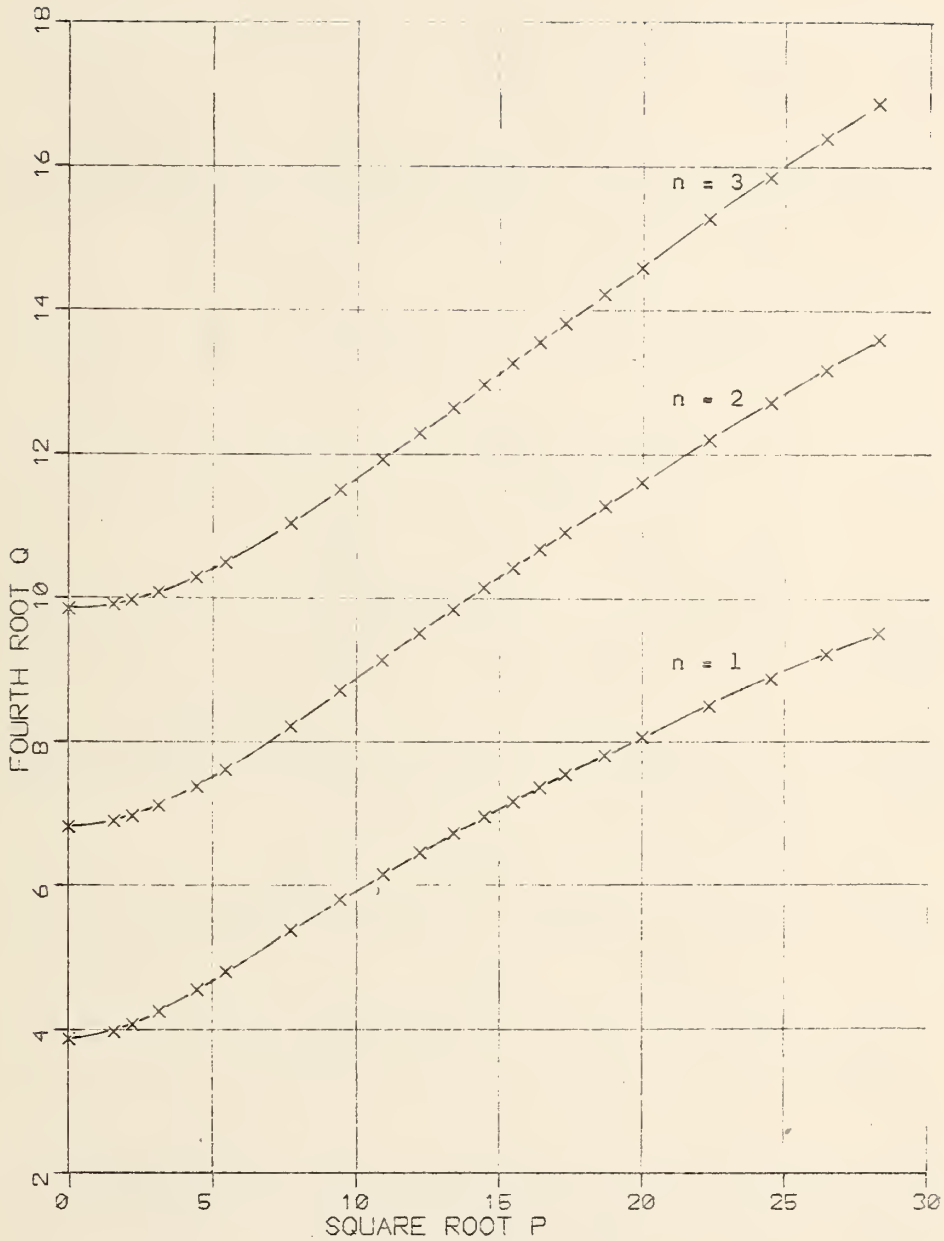
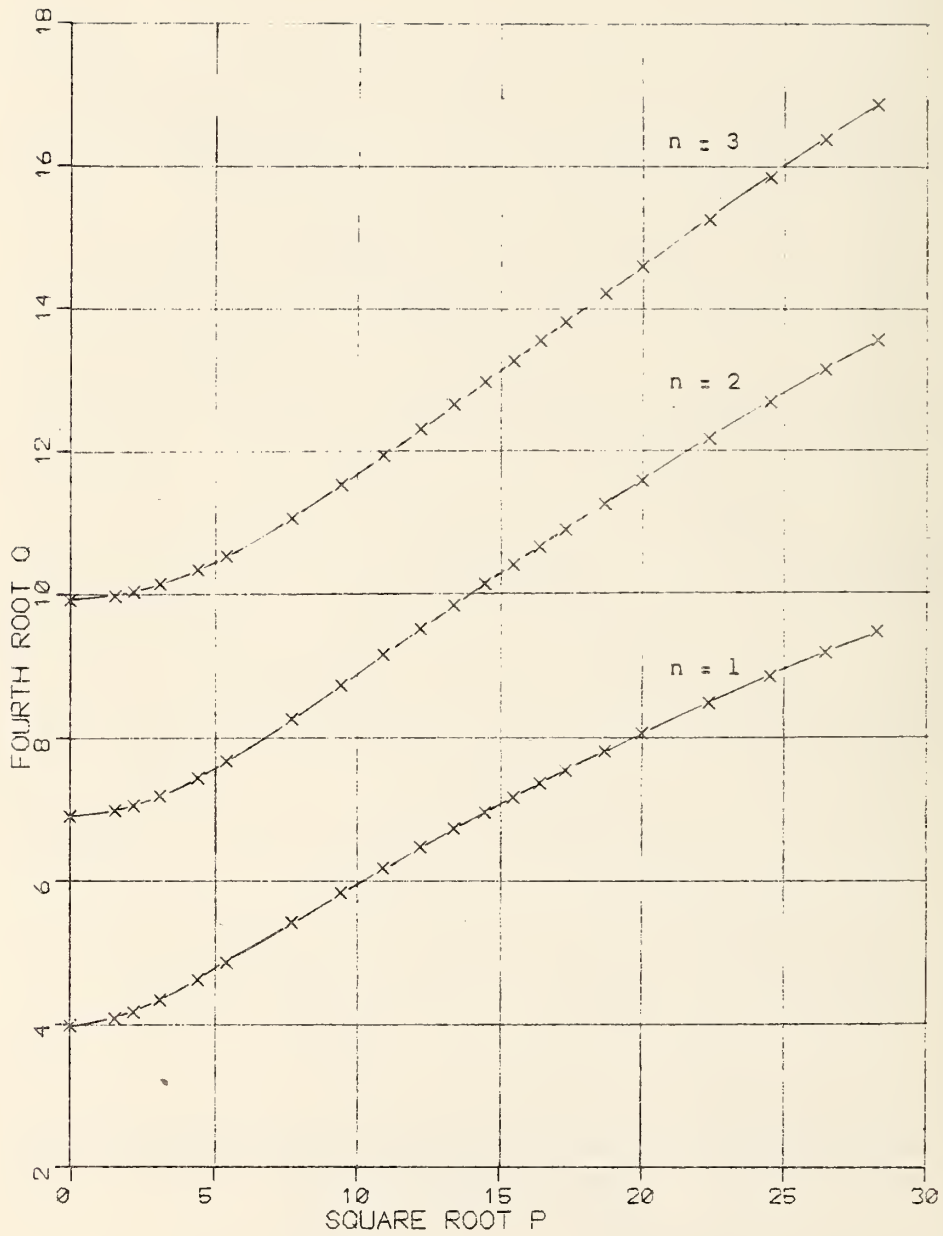


Fig. 47 $\sigma_1 = \sigma_2 = 5$



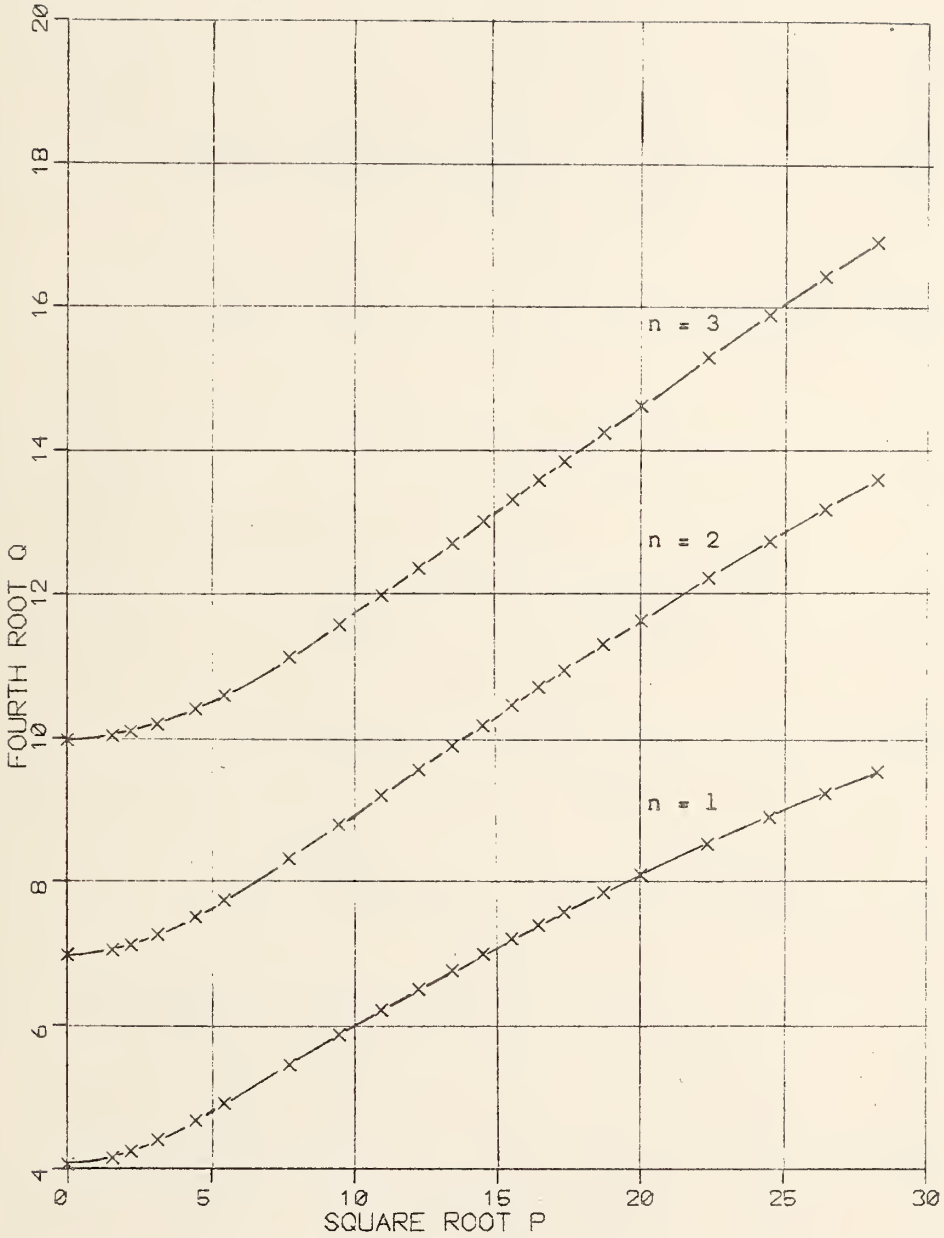
MODE OF VIBRATION = n

Fig. 48 $\sigma_1 = 10$, $\sigma_2 = 2$



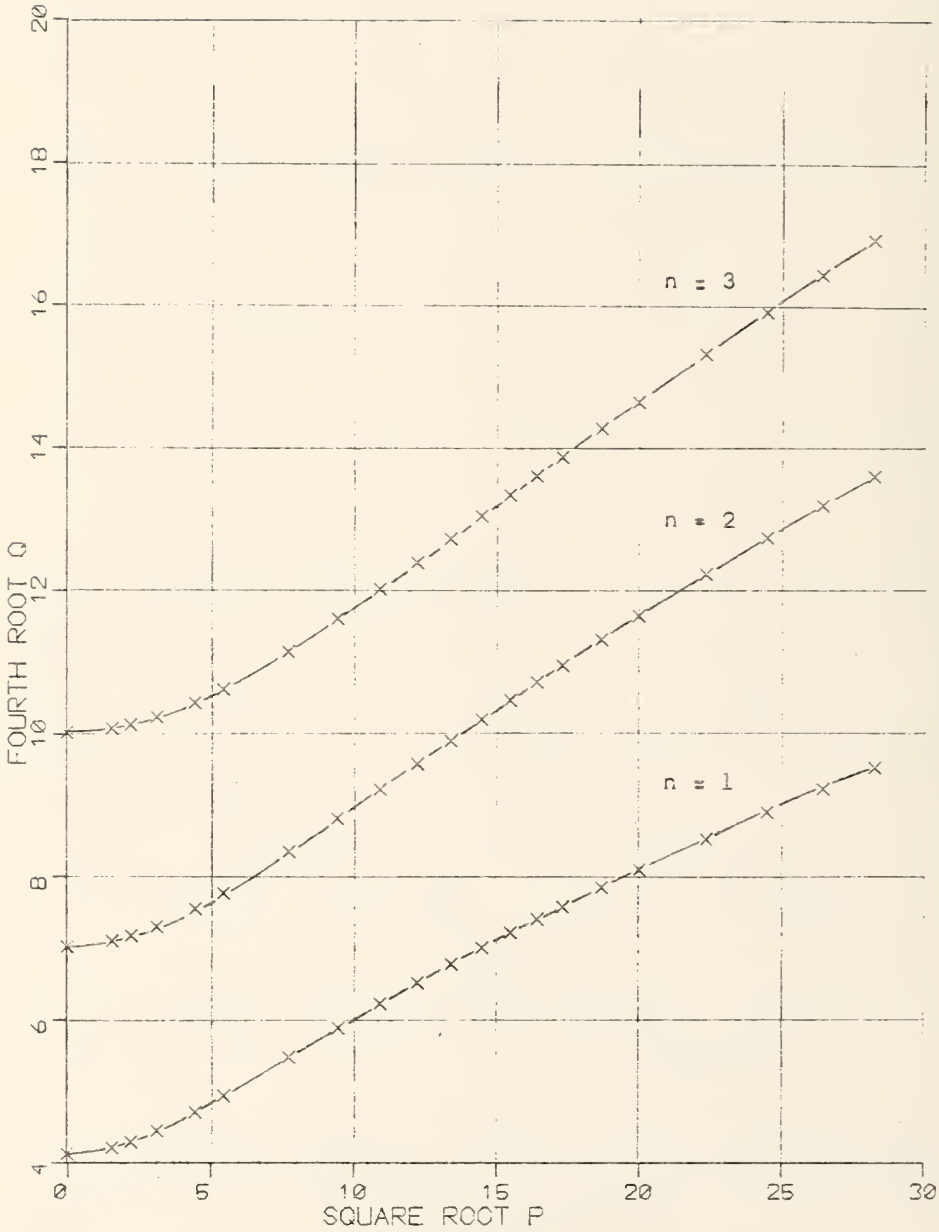
MODE OF VIBRATION = n

Fig.49 $\sigma_1 = 10$, $\sigma_2 = 4$



MODE OF VIBRATION = n

Fig. 50 $\sigma_1 = 10$, $\sigma_2 = 6$



MODE OF VIBRATION = n

Fig. 51 $\sigma_1 = 10$, $\sigma_2 = 8$

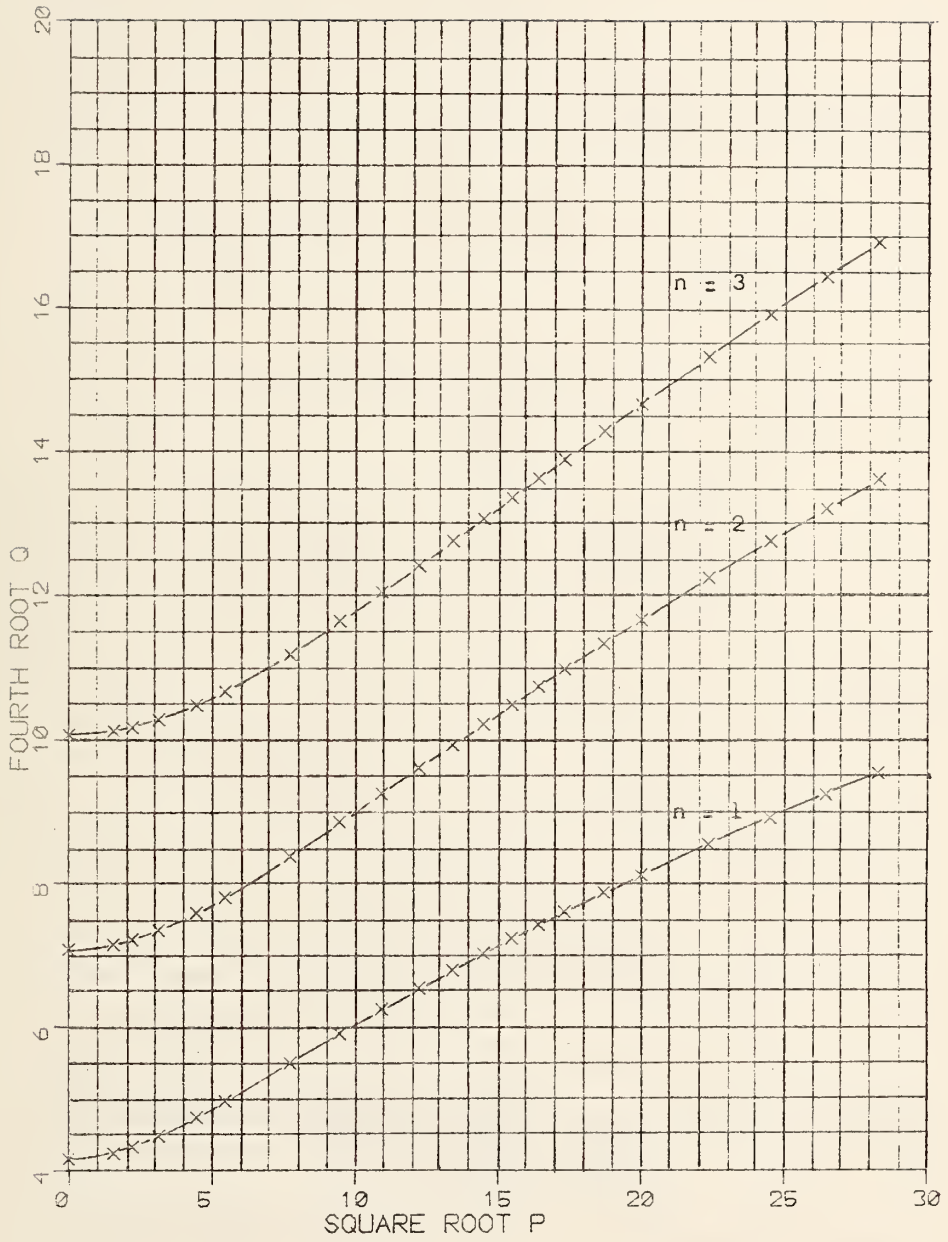
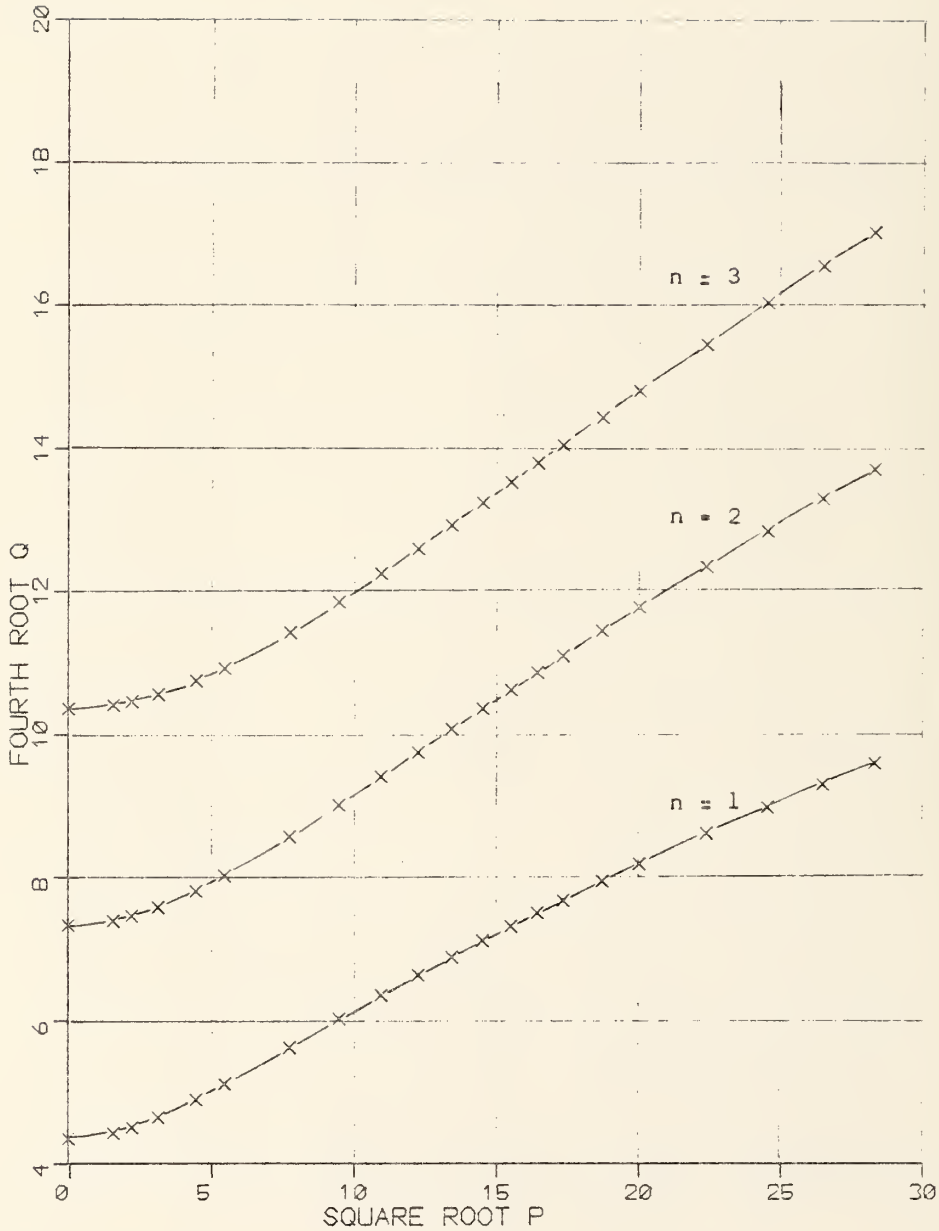
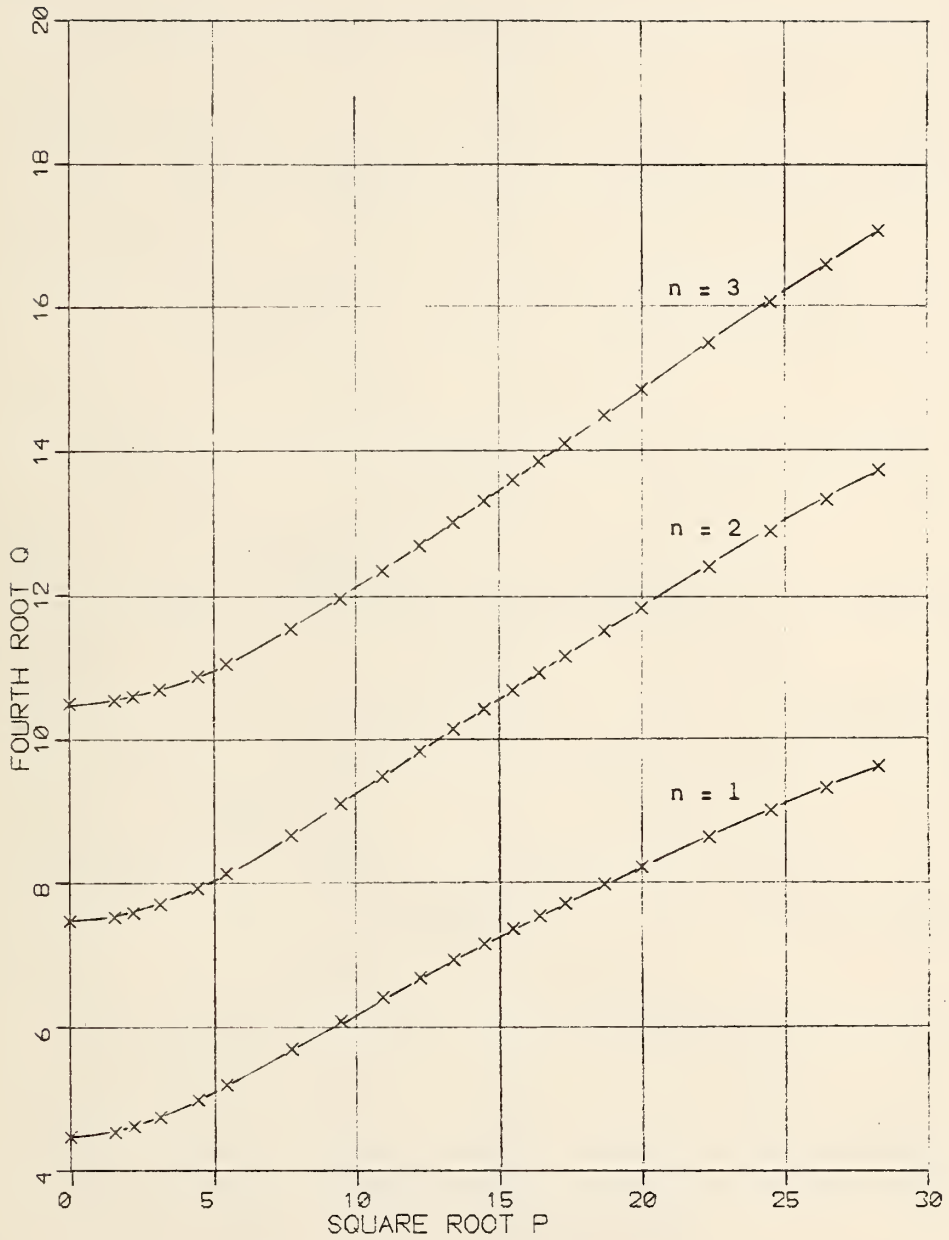


Fig. 52 $\sigma_1 = \sigma_2 = 10$



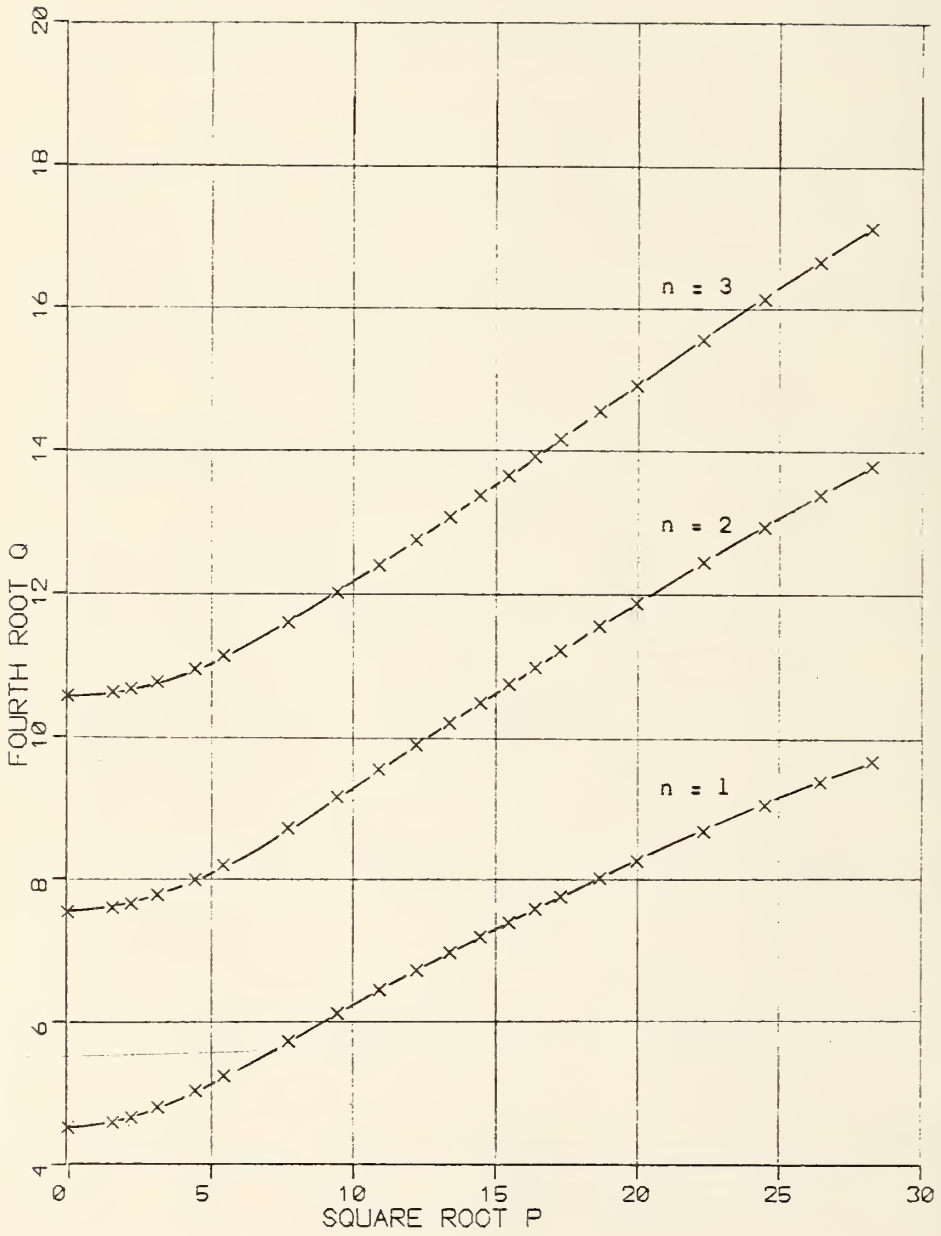
MODE OF VIBRATION = n

Fig. 53 $\sigma_1 = 50$, $\sigma_2 = 10$



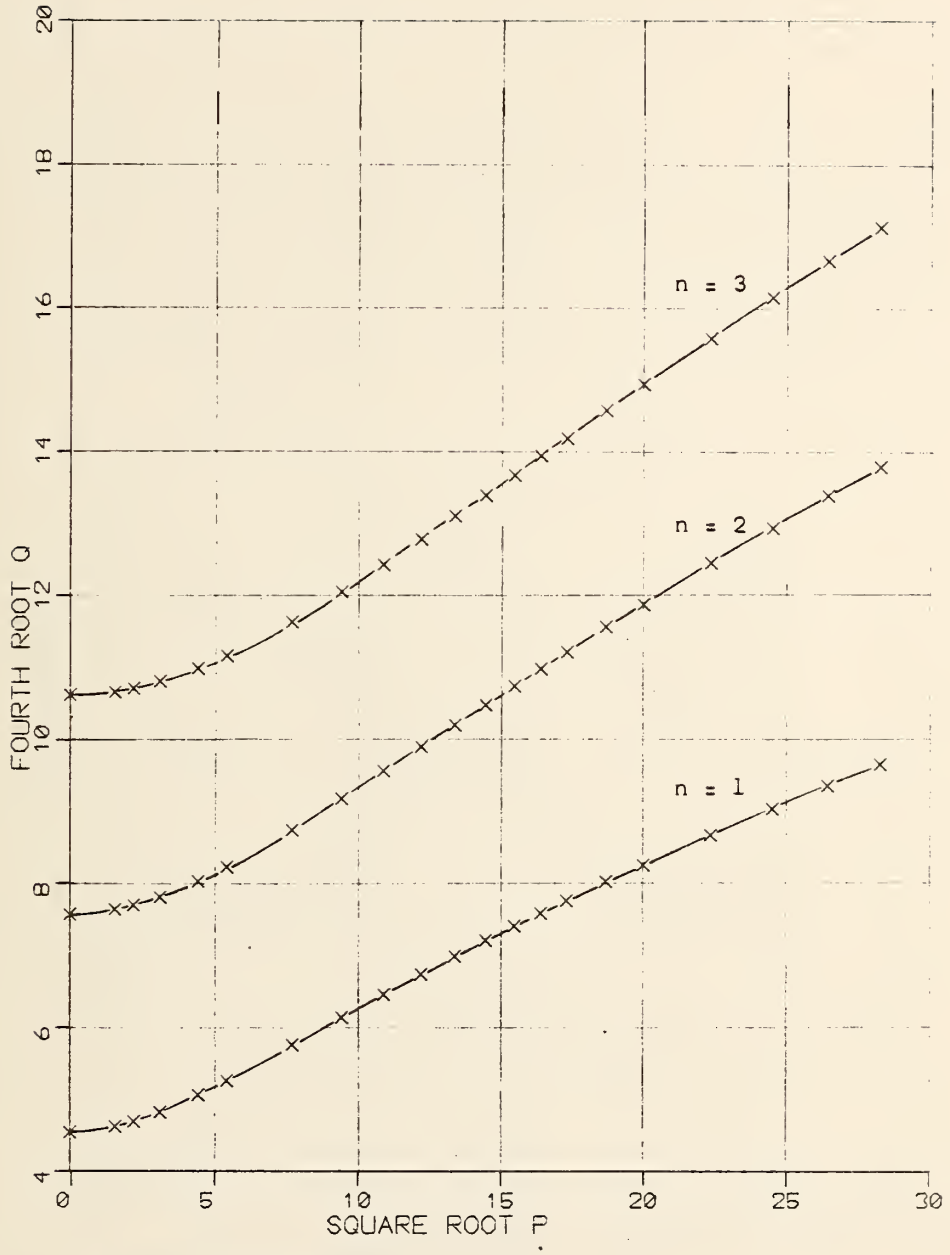
MODE OF VIBRATION = n

Fig. 54 $\sigma_1 = 50$, $\sigma_2 = 20$



MODE OF VIBRATION = n

Fig. 55 $\sigma_1 = 50$, $\sigma_2 = 30$



MODE OF VIBRATION = n

Fig. 56 σ_1 =50, σ_2 =40

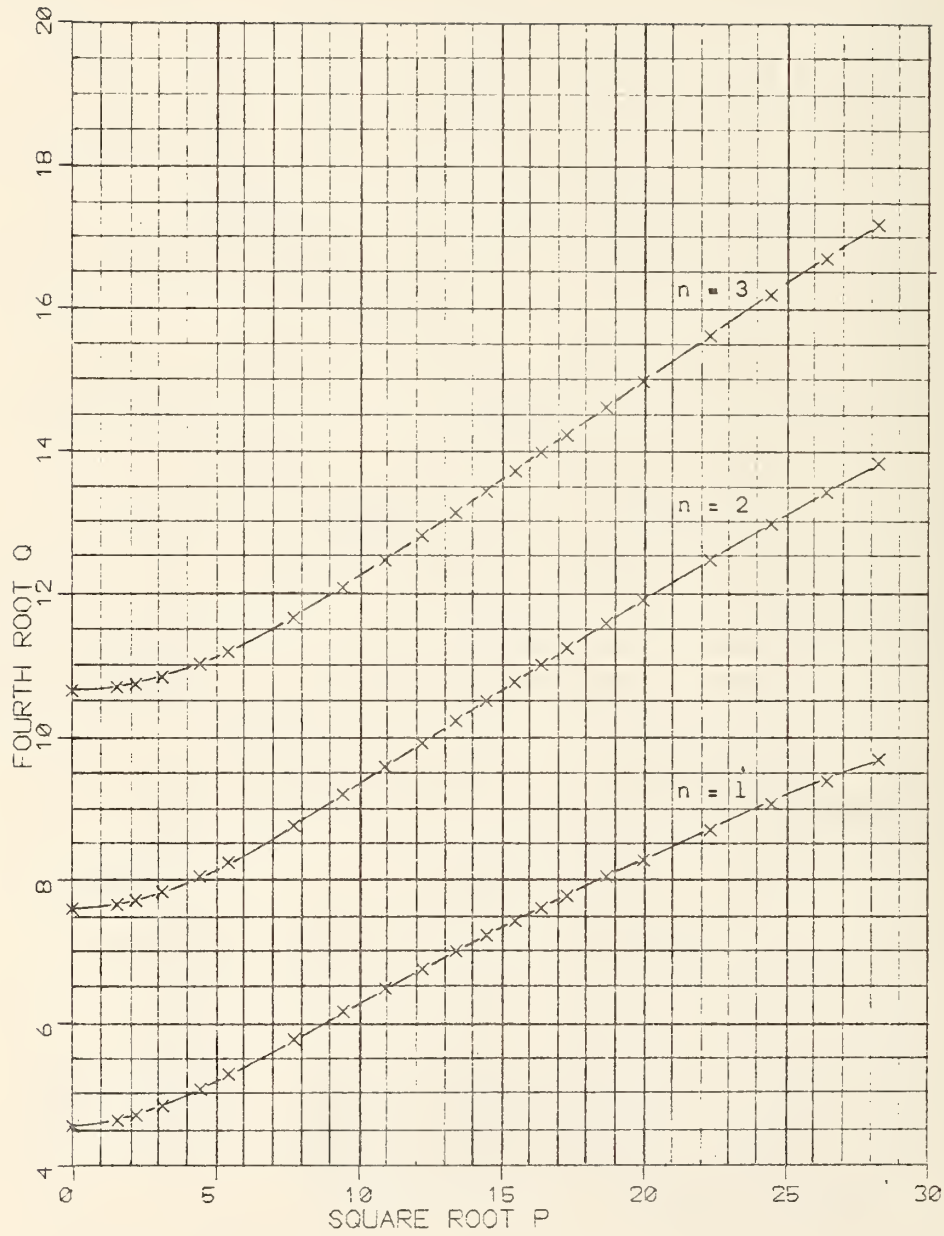
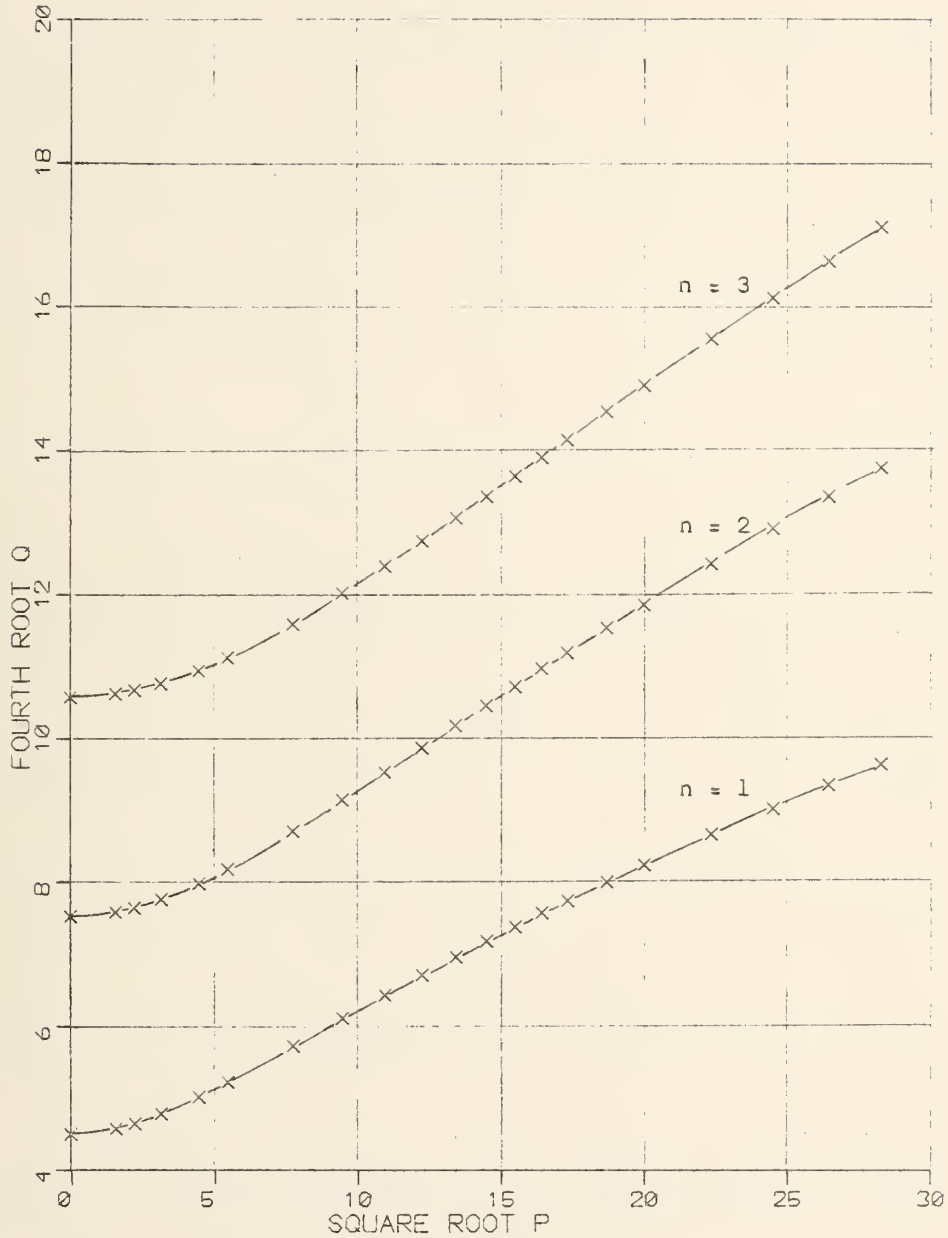
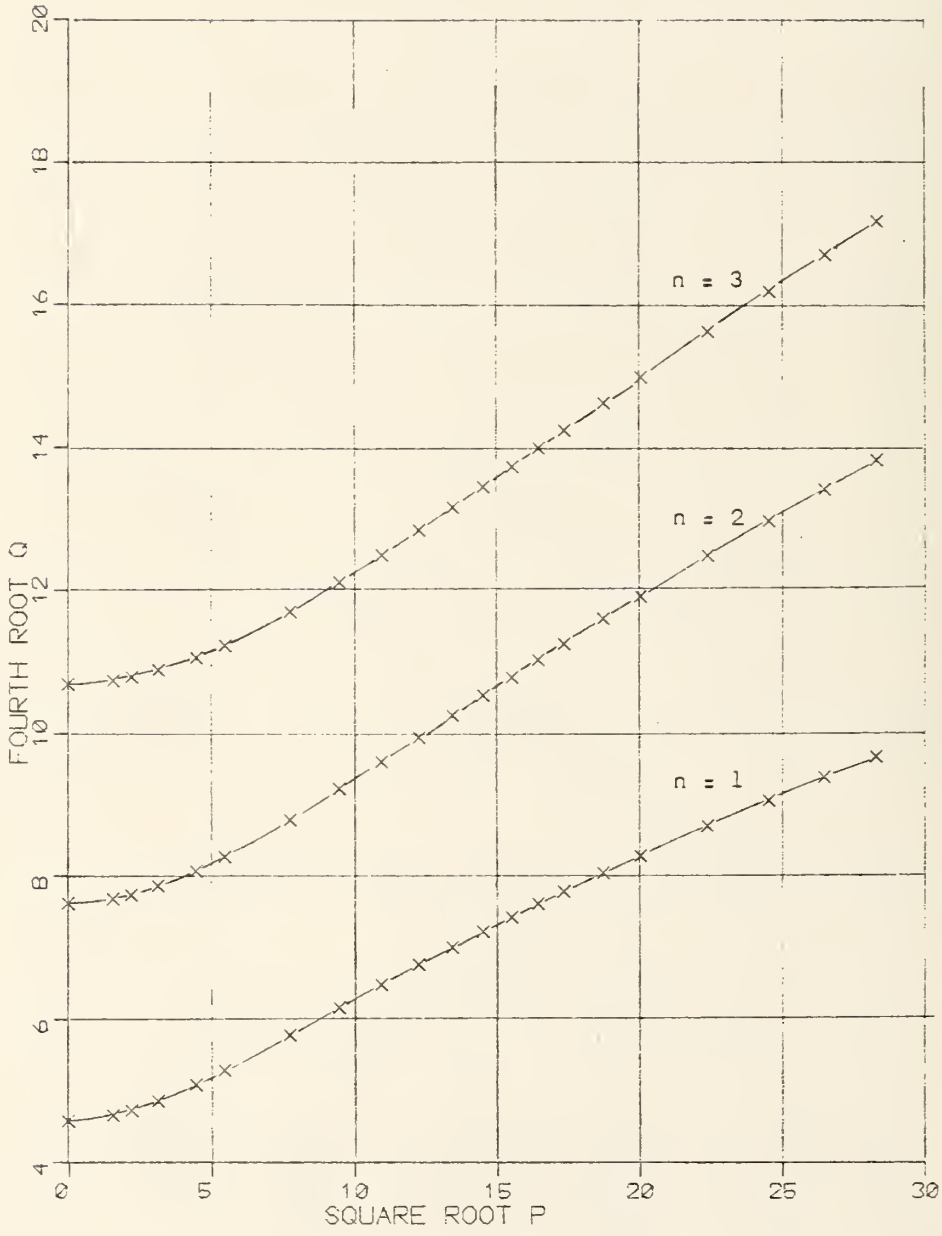


Fig. 57 $\sigma_1 = \sigma_2 = 50$



MODE OF VIBRATION = n

Fig. 58 $\sigma_1 = 100$, $\sigma_2 = 20$



MODE OF VIBRATION - n

Fig. 59 $\sigma_1 = 100, \quad \sigma_2 = 40$

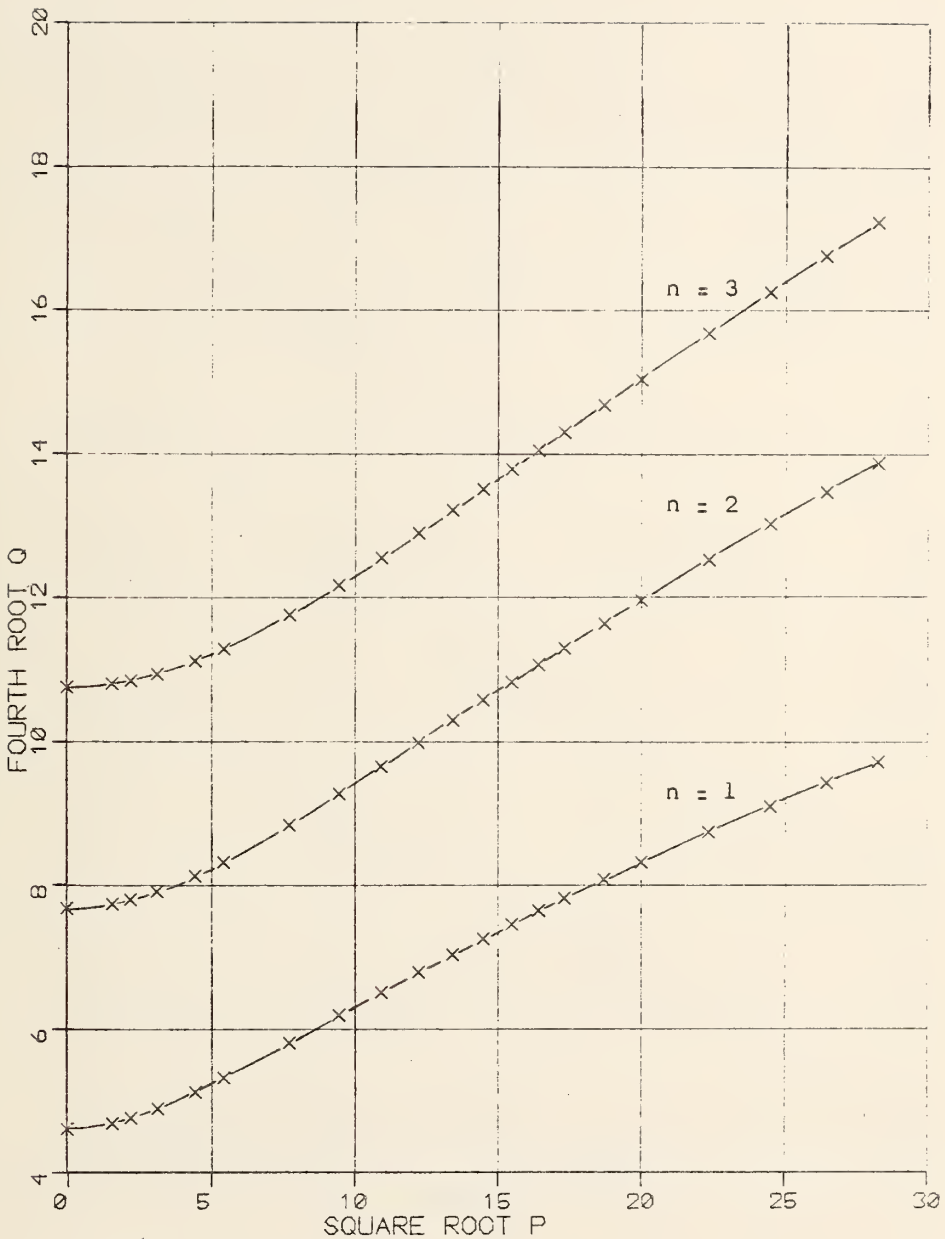
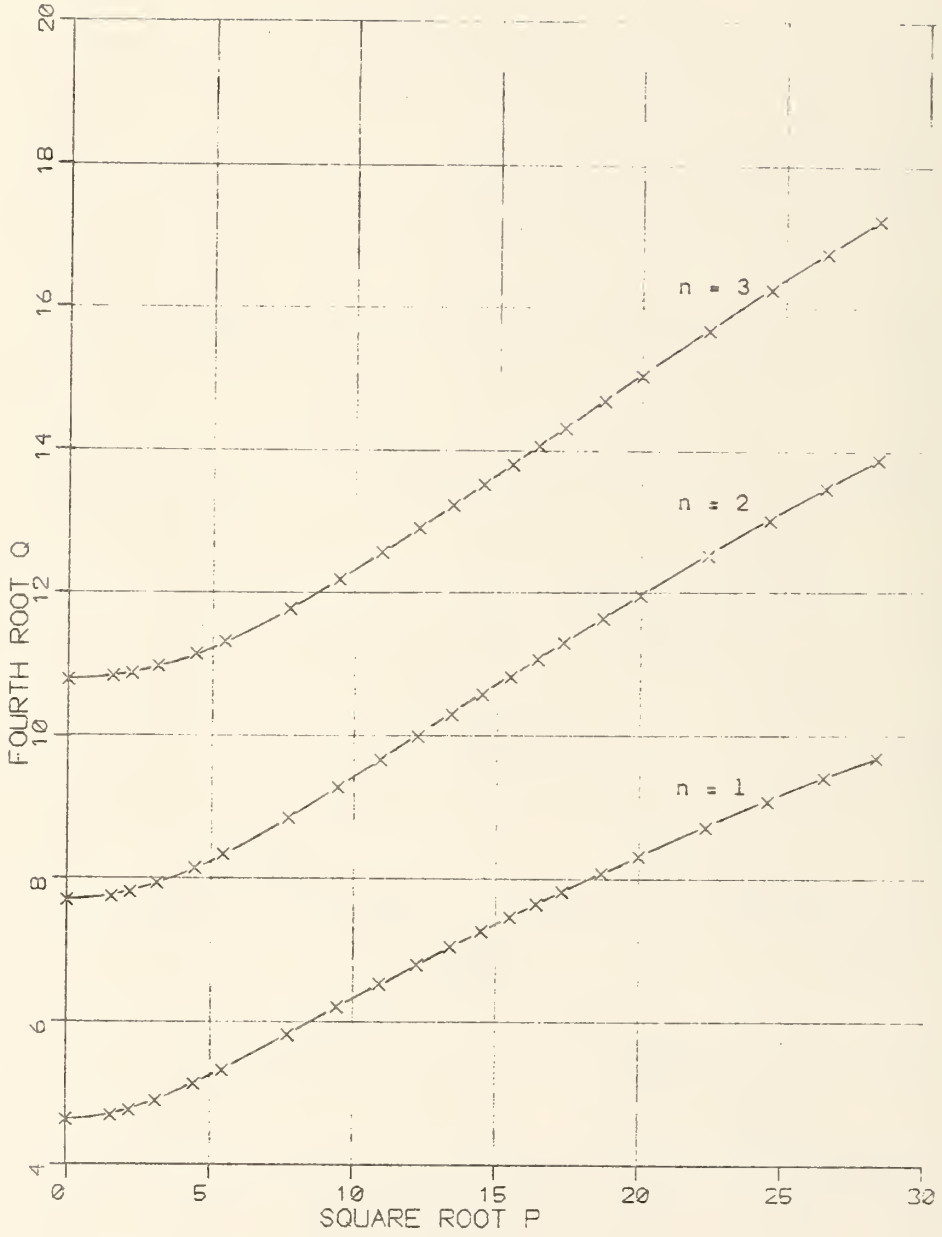


Fig. 60 $\sigma_1 = 100, \quad \sigma_2 = 60$



MODE OF VIBRATION = n

Fig. 61 $\sigma_1 = 100$, $\sigma_2 = 80$

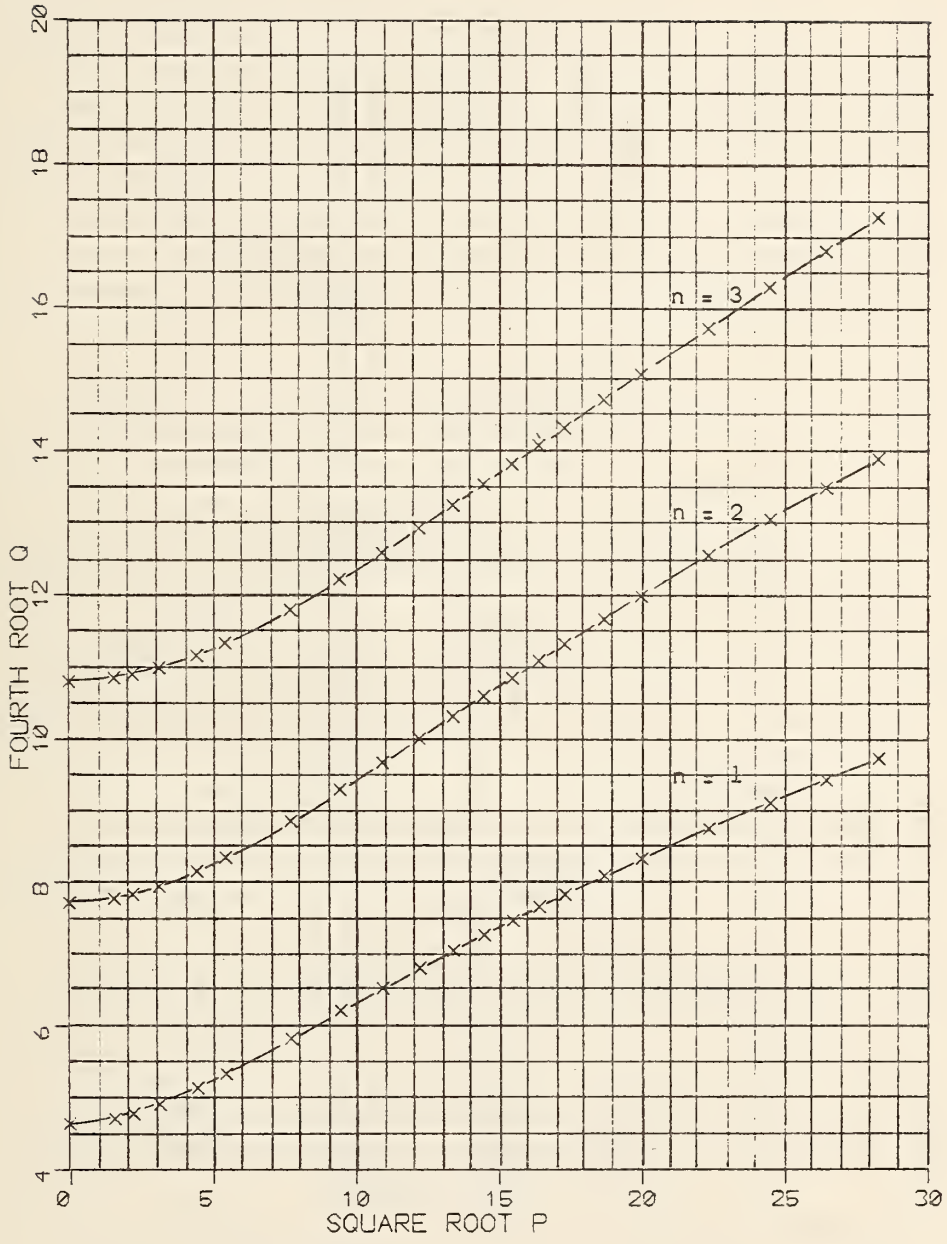
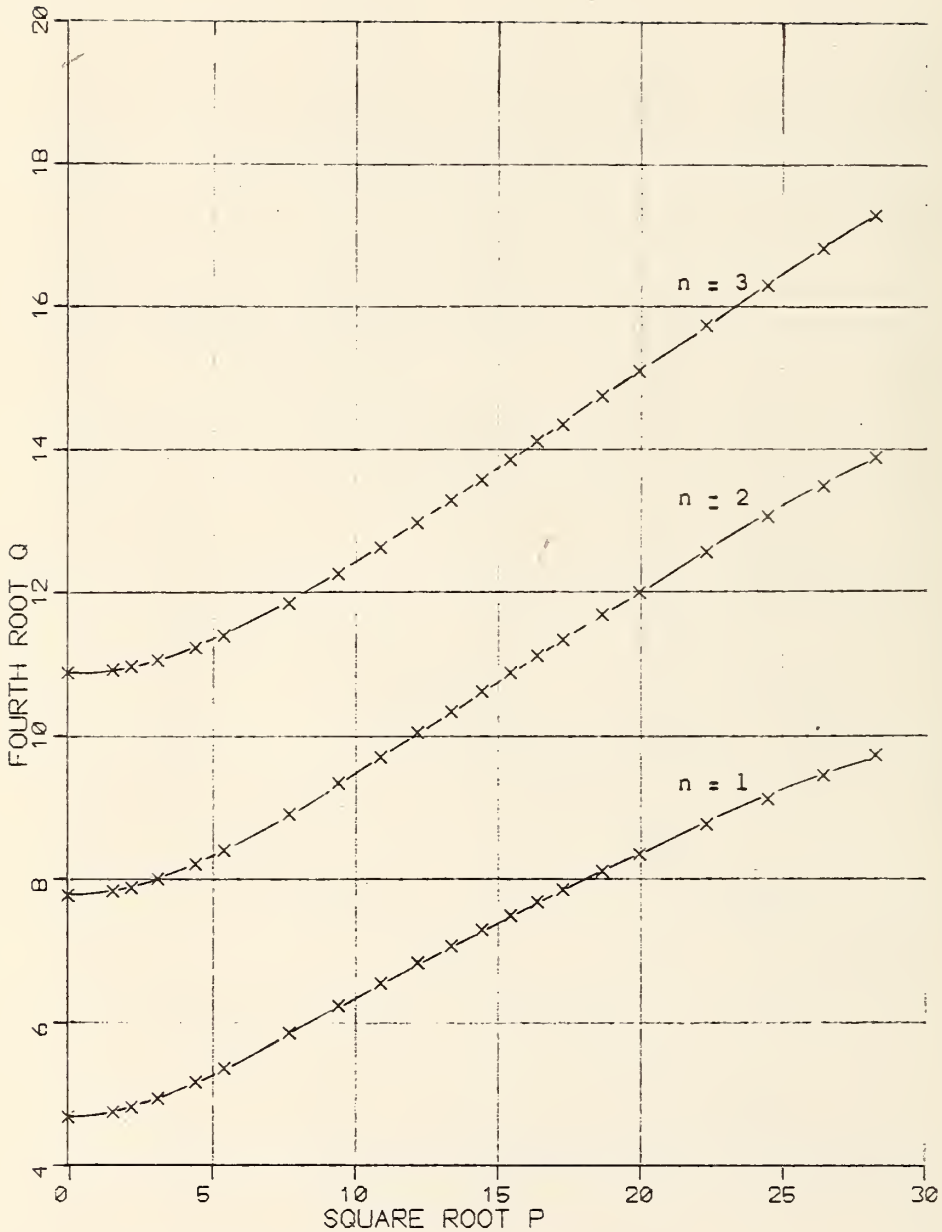
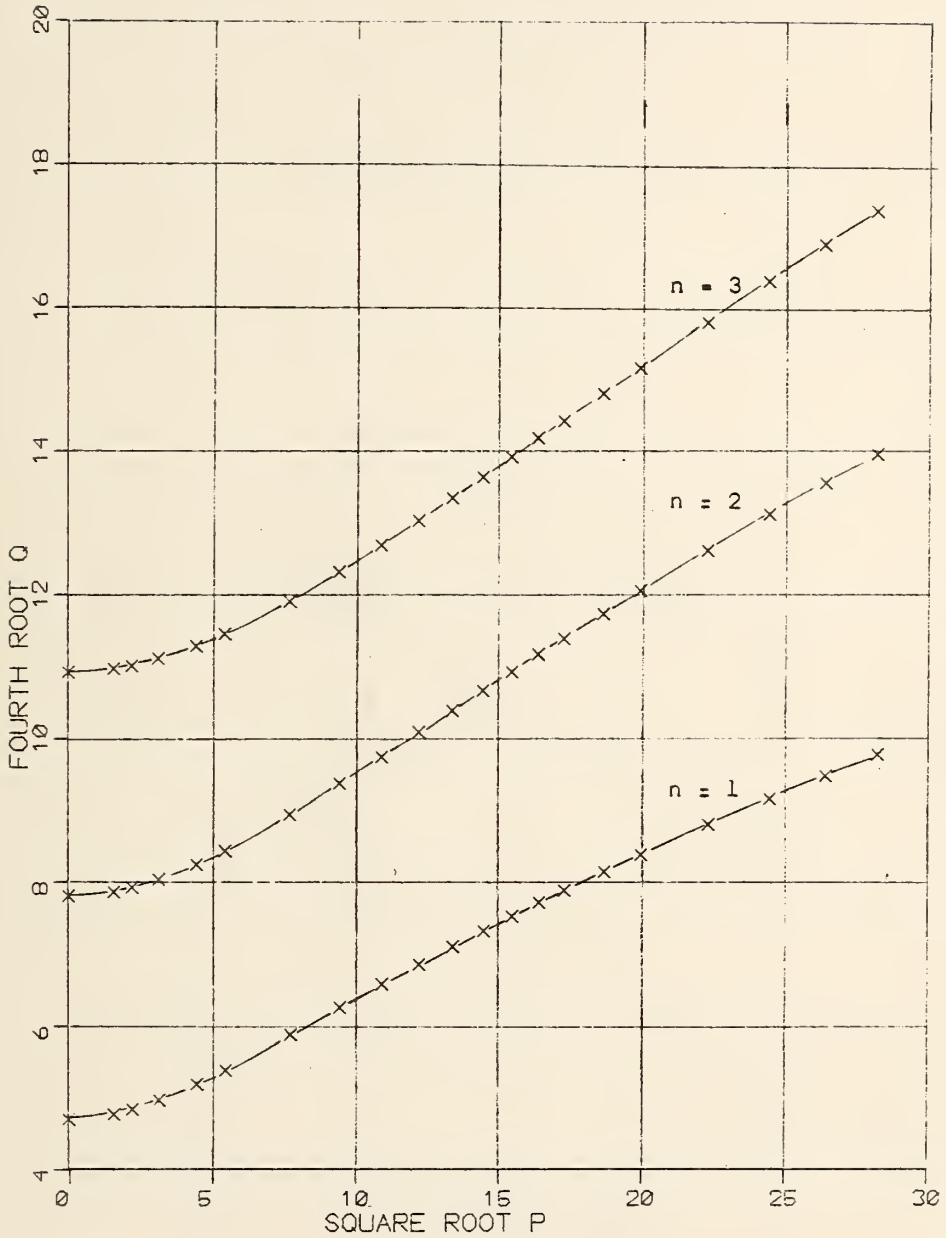


Fig. 62 $\sigma_1 = \sigma_2 = 100$



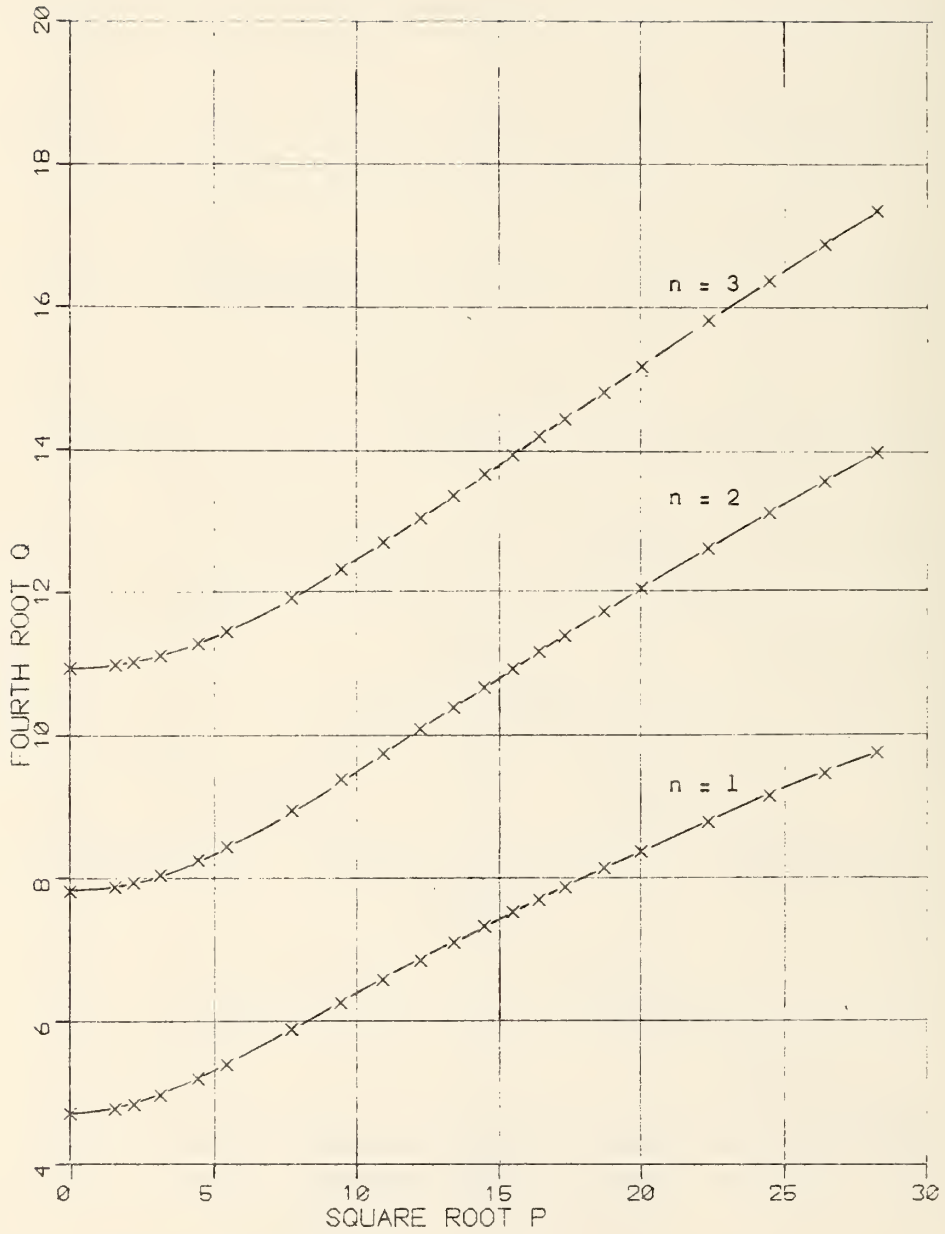
MODE OF VIBRATION = n

Fig. 63 $\sigma_1 = 500$, $\sigma_2 = 100$



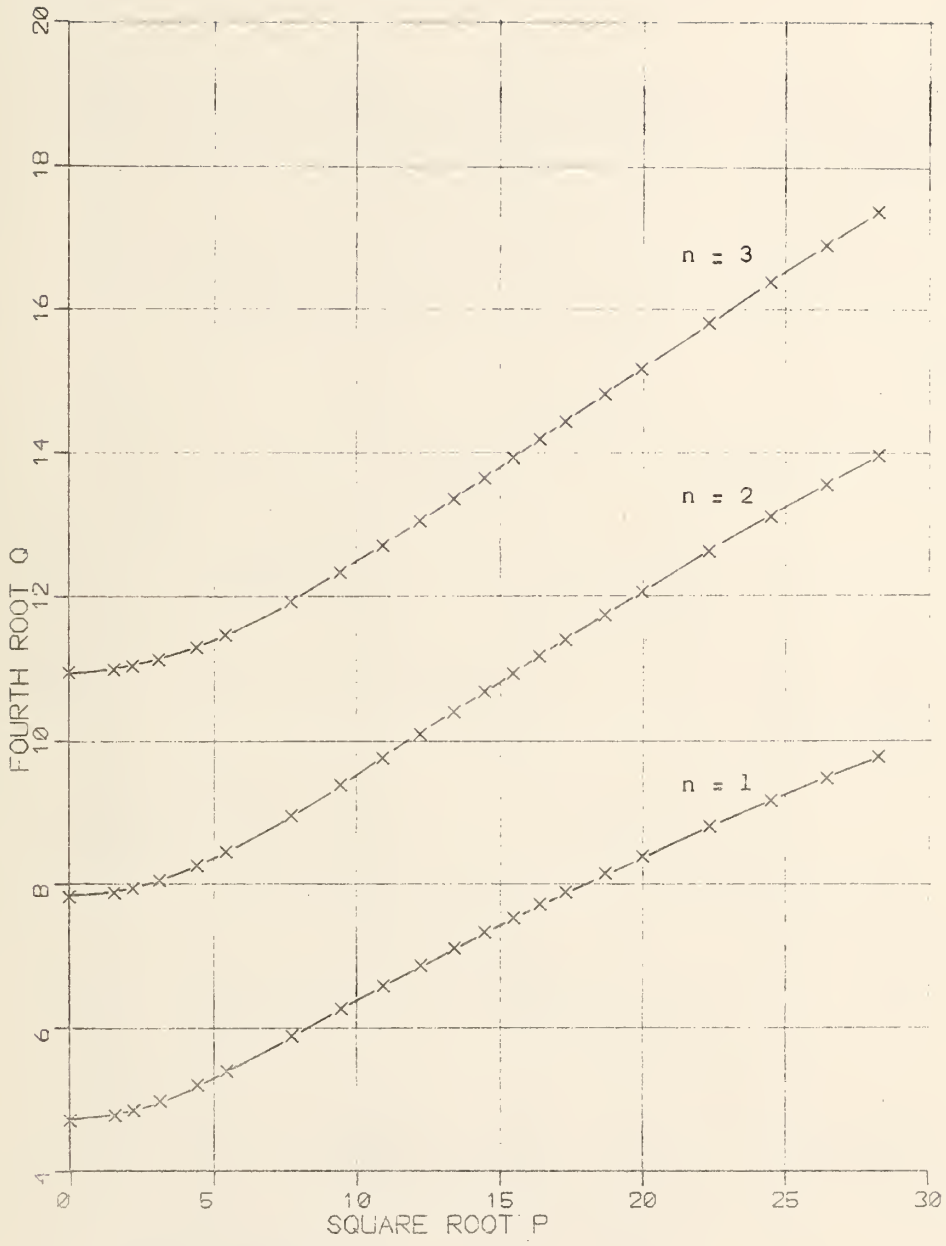
MODE OF VIBRATION = n

Fig. 64 $\sigma_1 = 500$, $\sigma_2 = 200$



MODE OF VIBRATION = n

Fig. 65 $\sigma_1 = 500$, $\sigma_2 = 300$



MODE OF VIBRATION = n

Fig. 66 $\sigma_1 = 500, \quad \sigma_2 = 400$

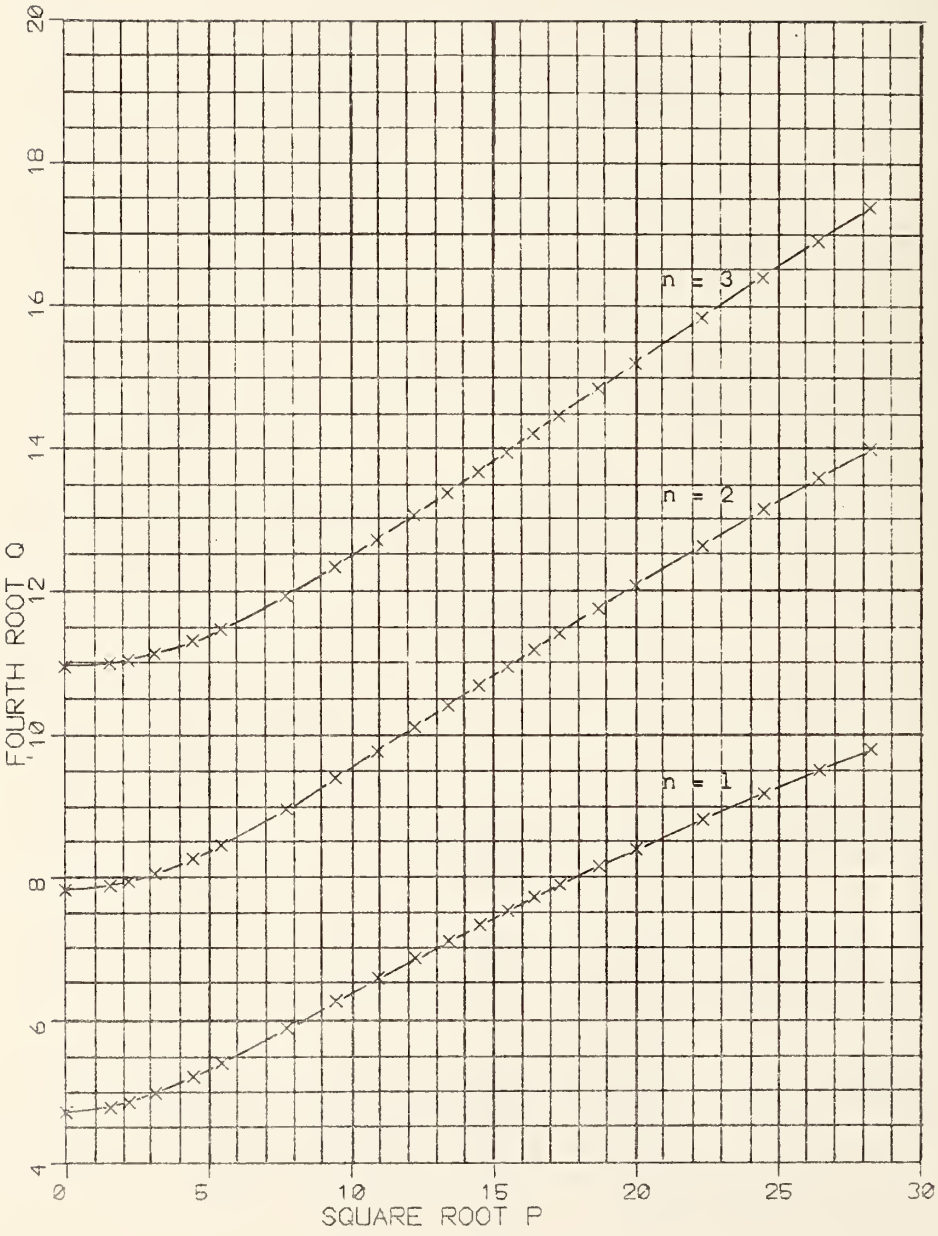
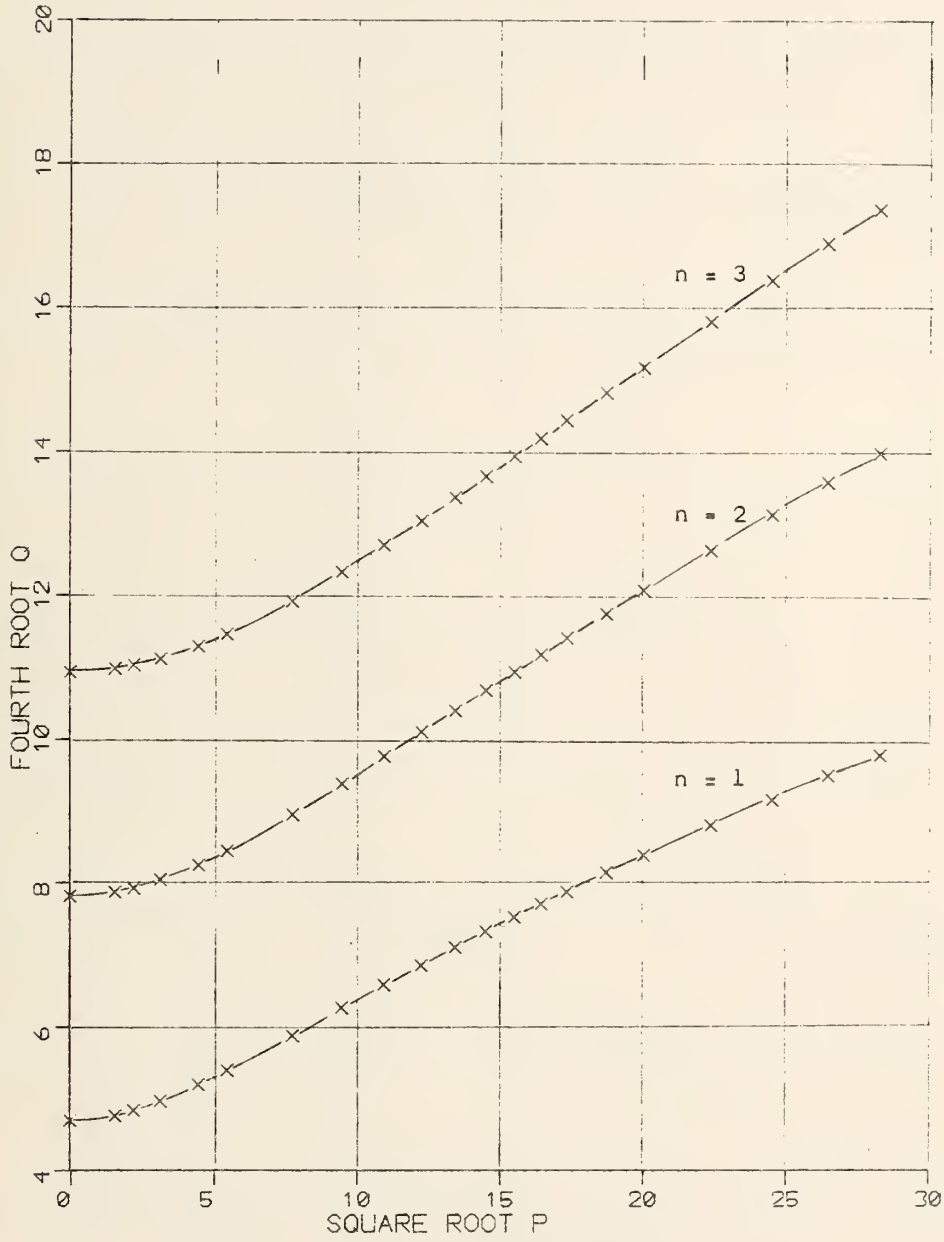
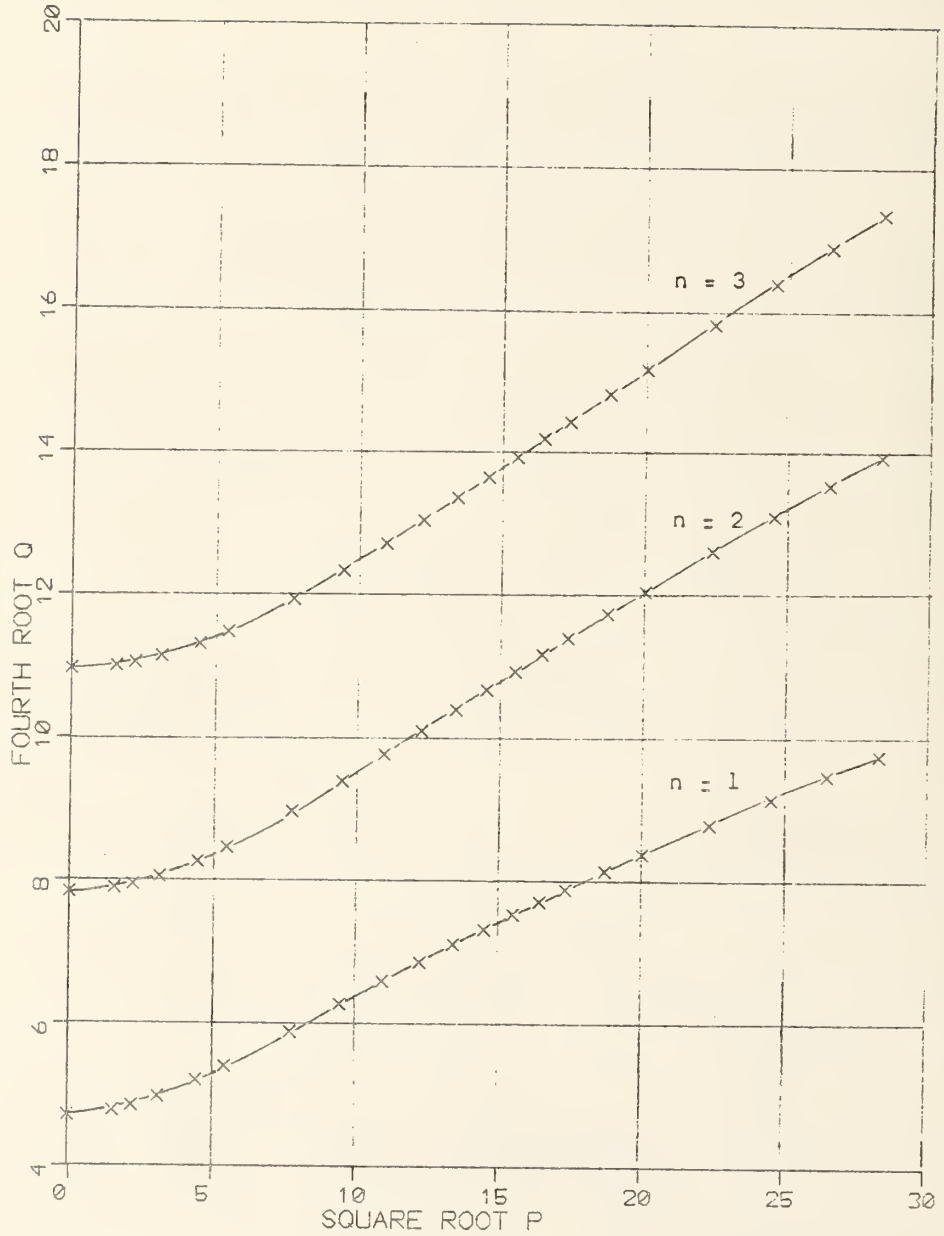


Fig. 67 $\sigma_1 = \sigma_2 = .500$



MODE OF VIBRATION = n

Fig. 68 σ_1= 1,000 σ_2= 200



MODE OF VIBRATION = n

Fig. 69 $\sigma_1 = 1{,}000$ $\sigma_2 = 400$

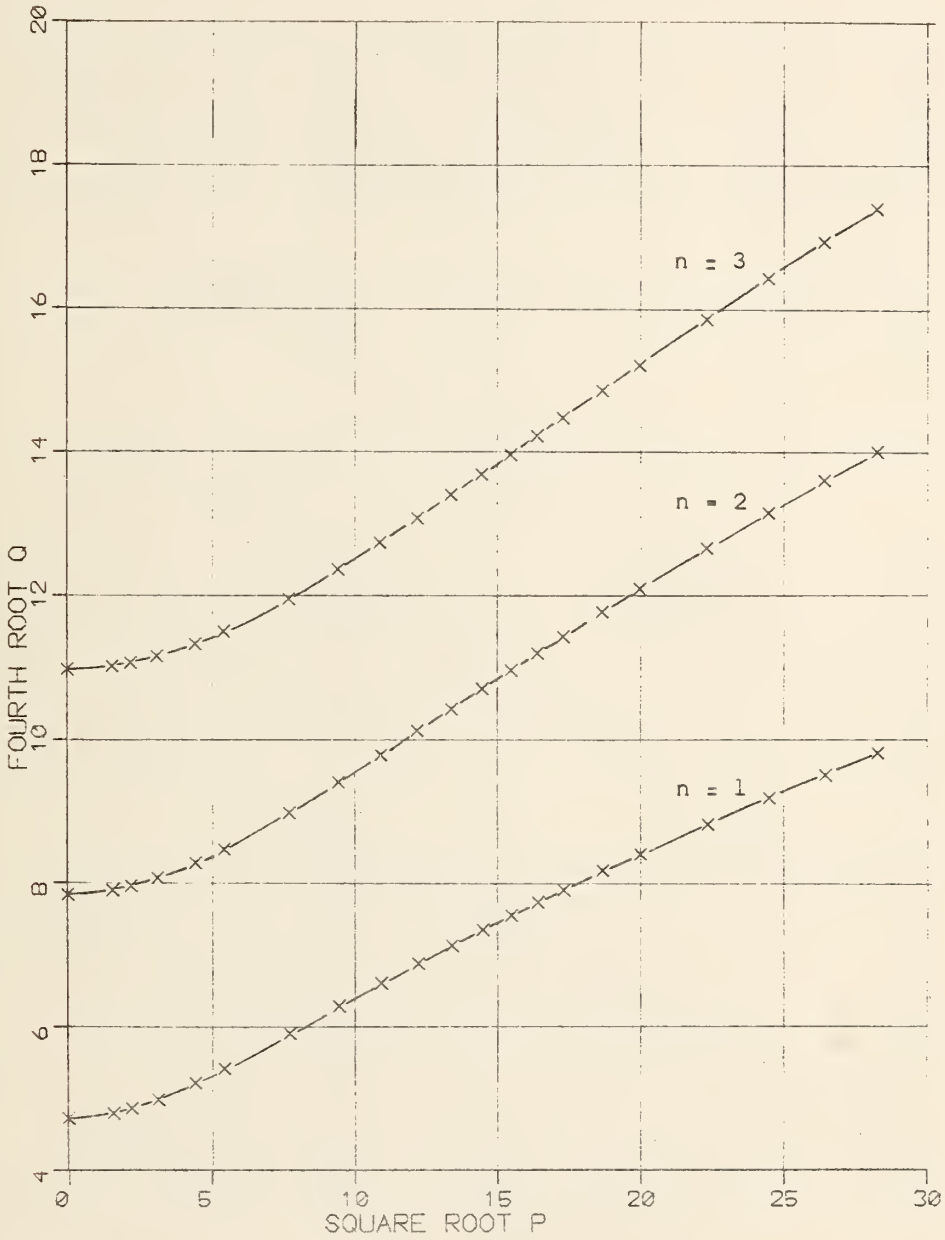
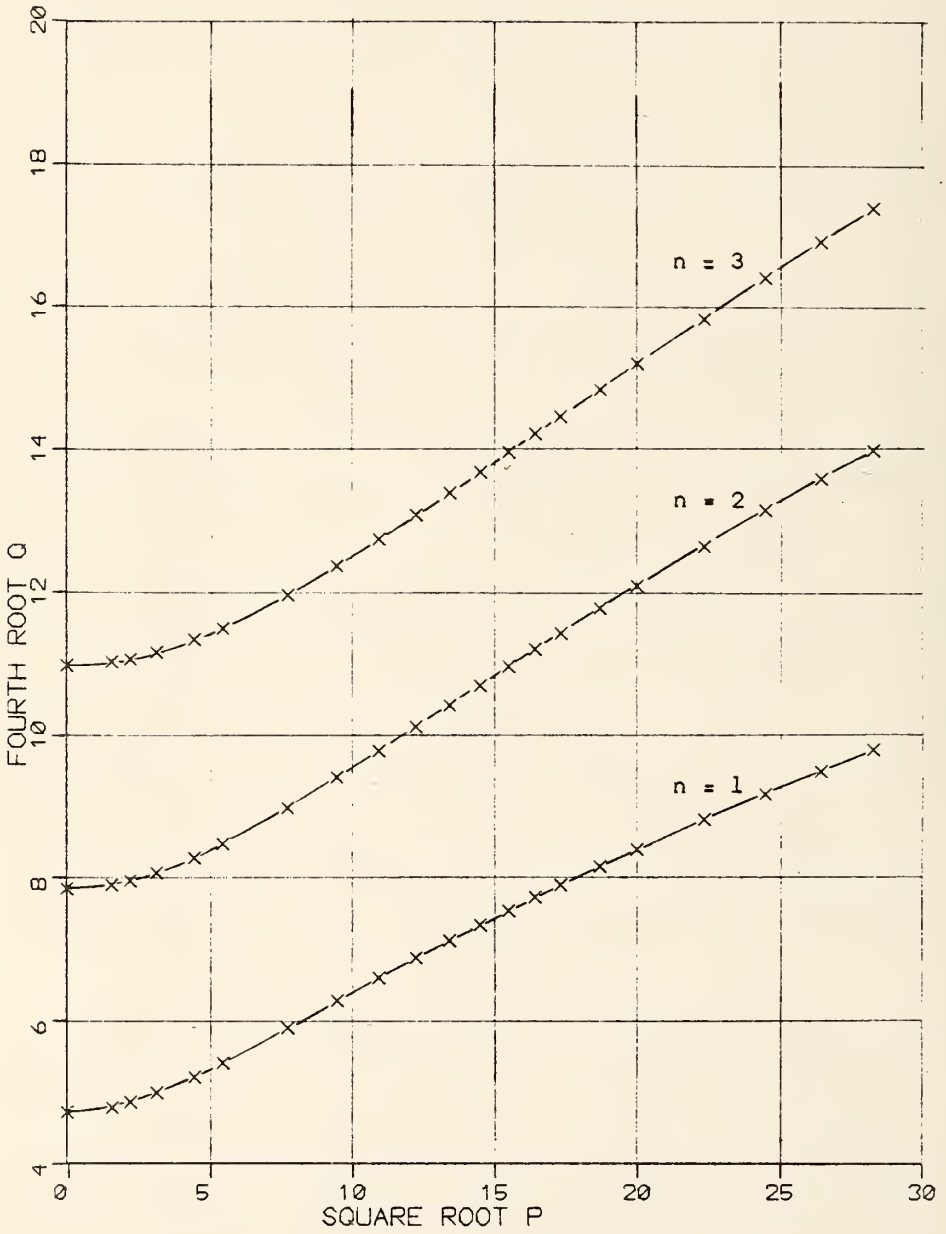


Fig. 70 σ_1= 1,000 σ_2= 600



MODE OF VIBRATION = n

Fig. 71 $\sigma_1 = \sigma_2 = 1{,}000$

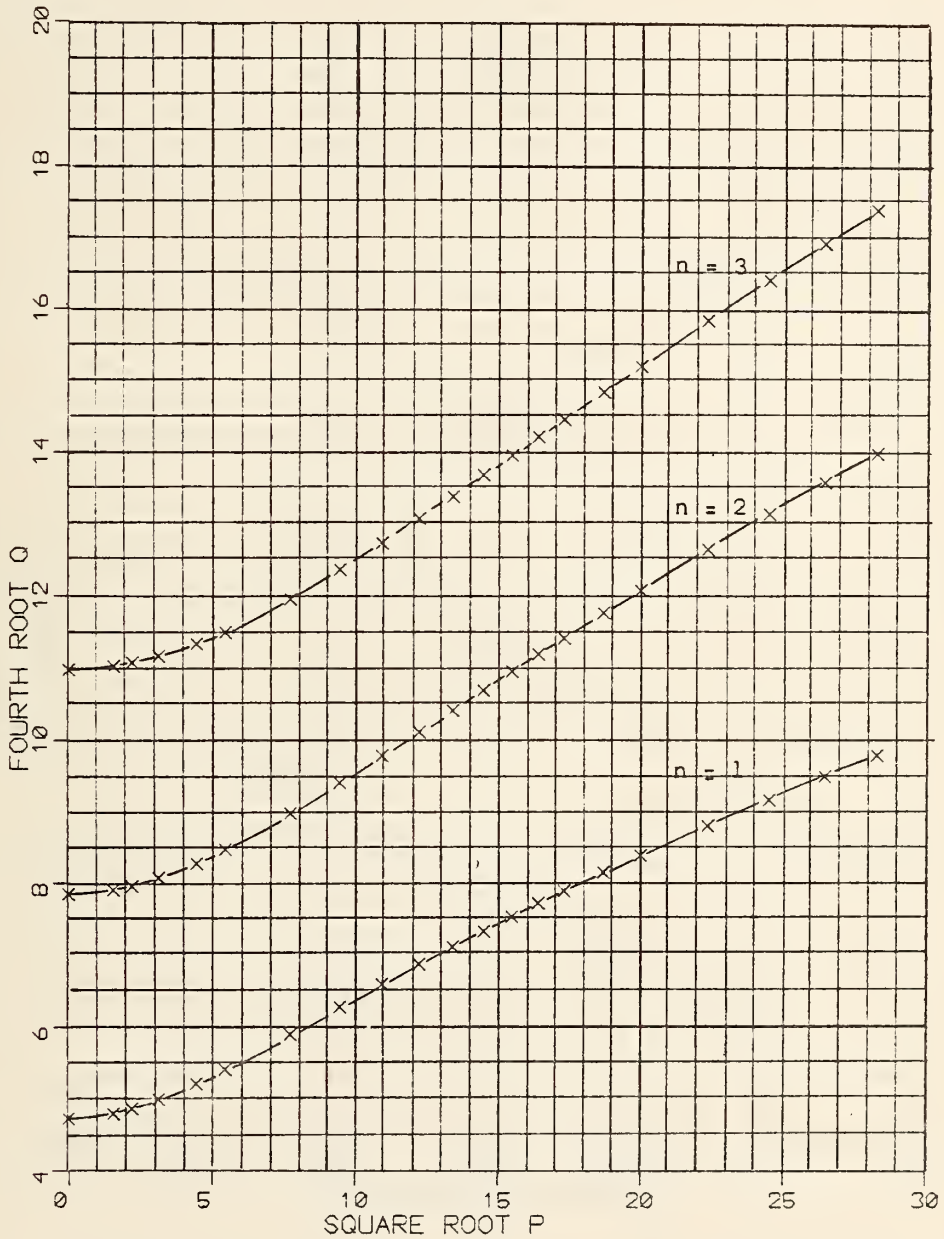
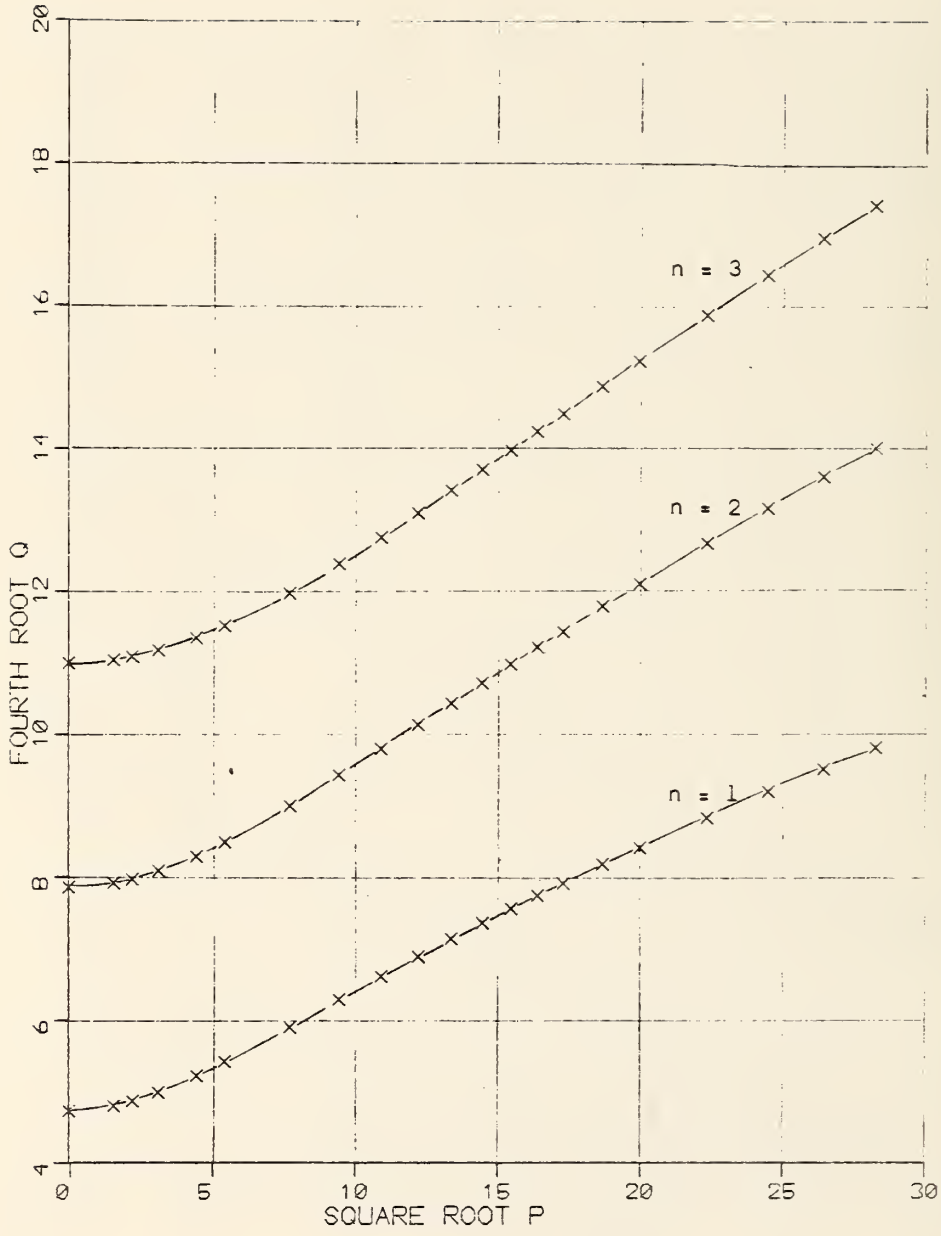
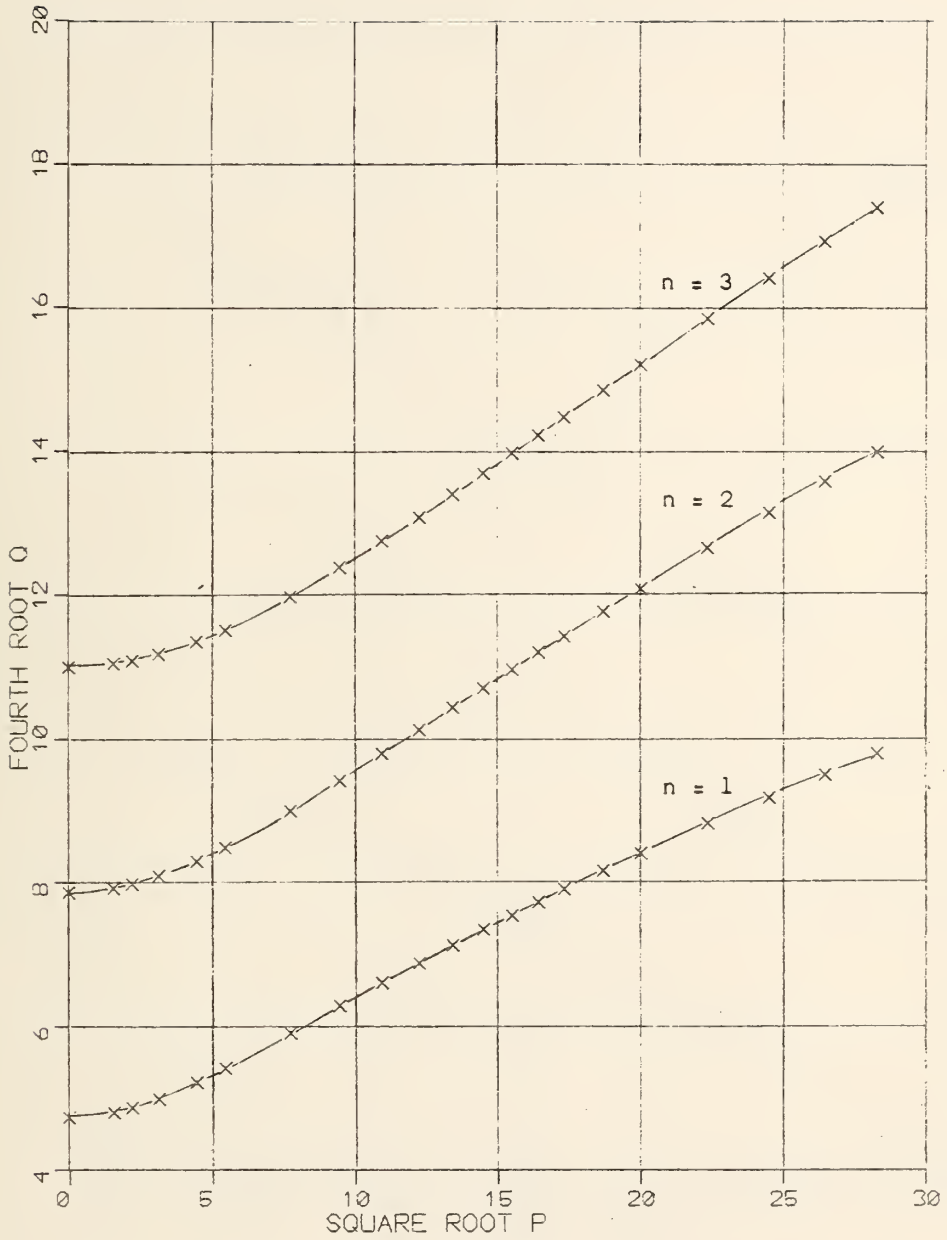


Fig. 72 $\sigma_1 = \sigma_2 = 1{,}000$



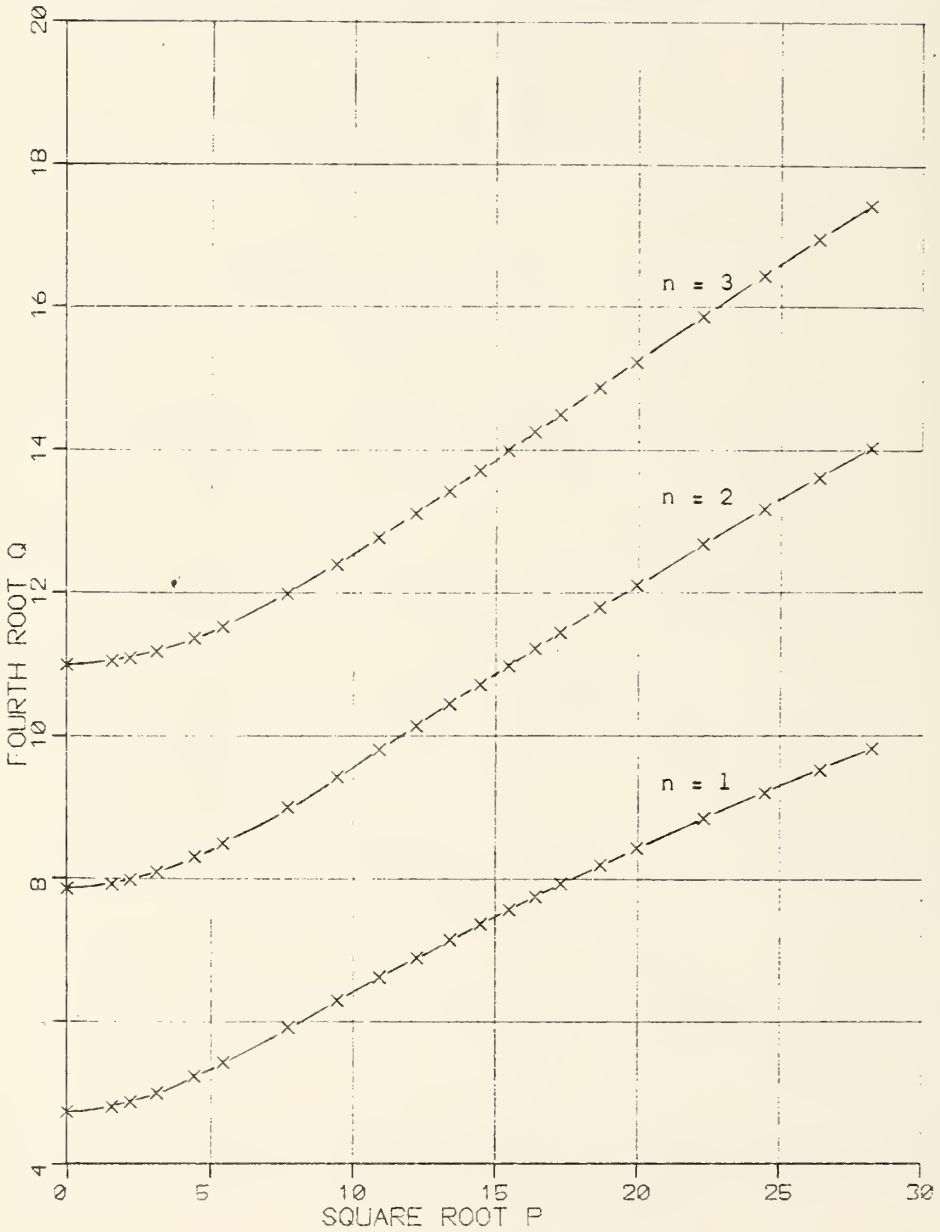
MODE OF VIBRATION = n

Fig. 73 σ_1= 10,000,σ_2= 2,000



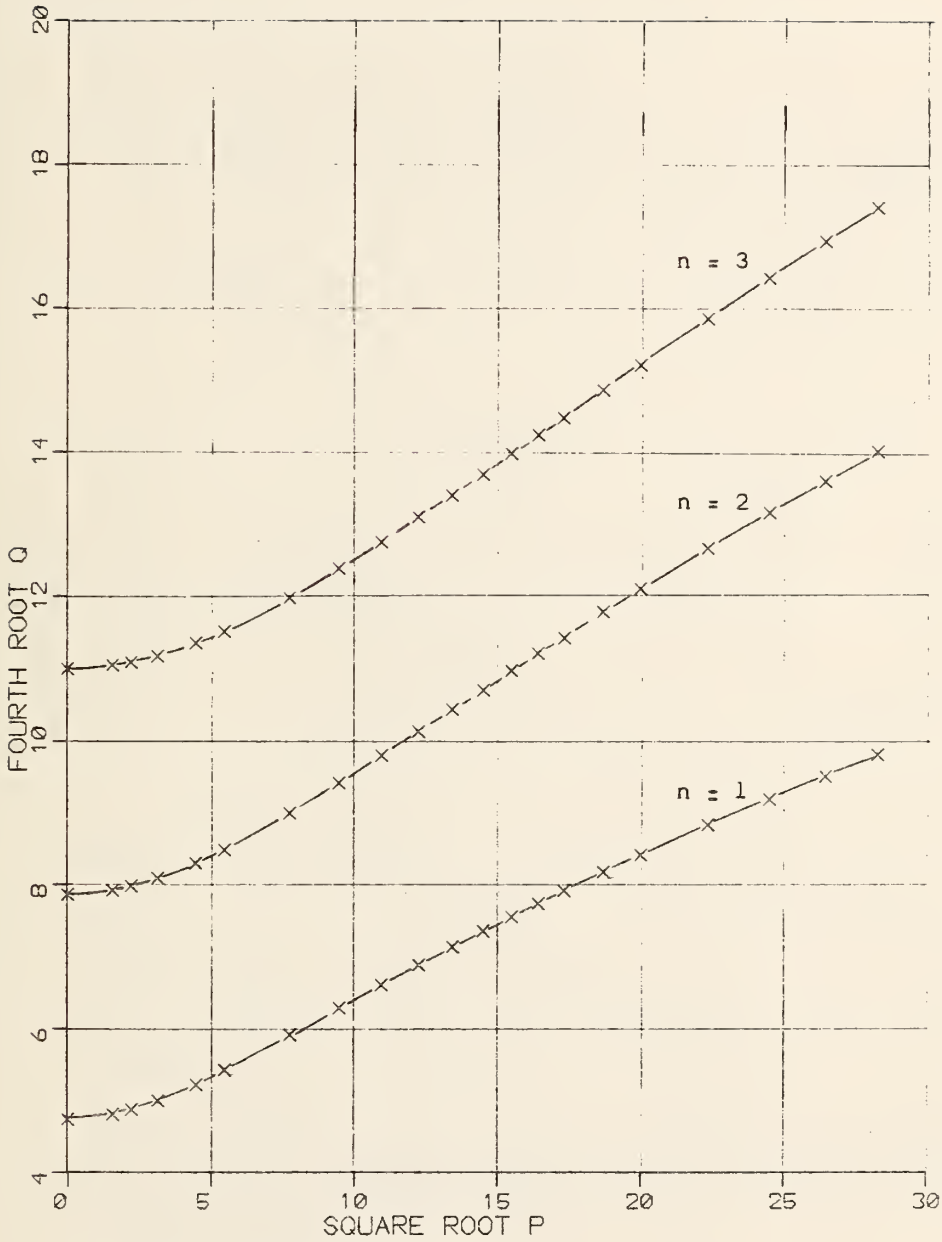
MODE OF VIBRATION = n

Fig. 74 $\sigma_1 = 10{,}000$, $\sigma_2 = 4{,}000$



MODE OF VIBRATION = n

Fig. 75 σ_1= 10,000, σ_2= 6,000



MODE OF VIBRATION = n

Fig. 76 σ_1= 10,000, σ_2= 8,000

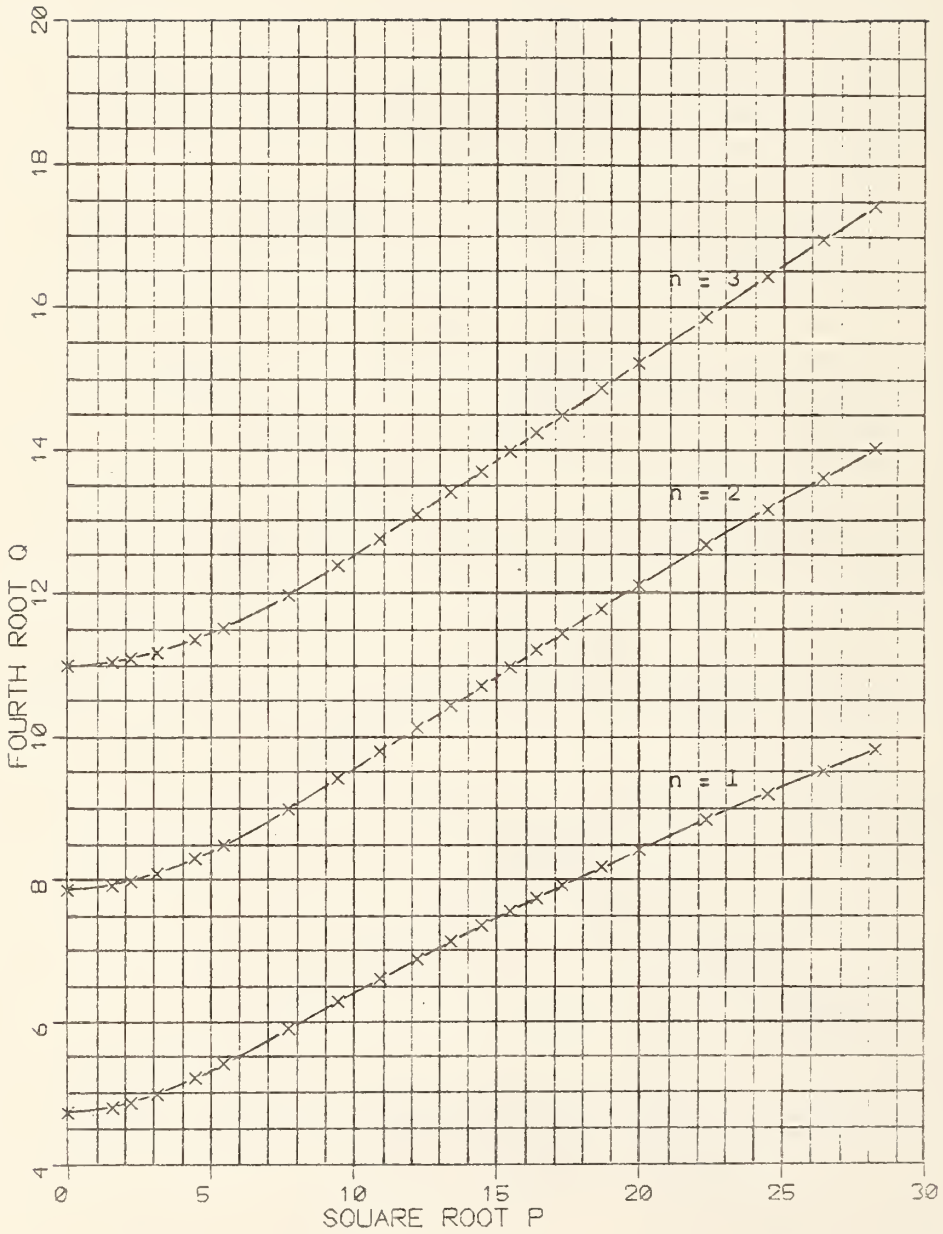
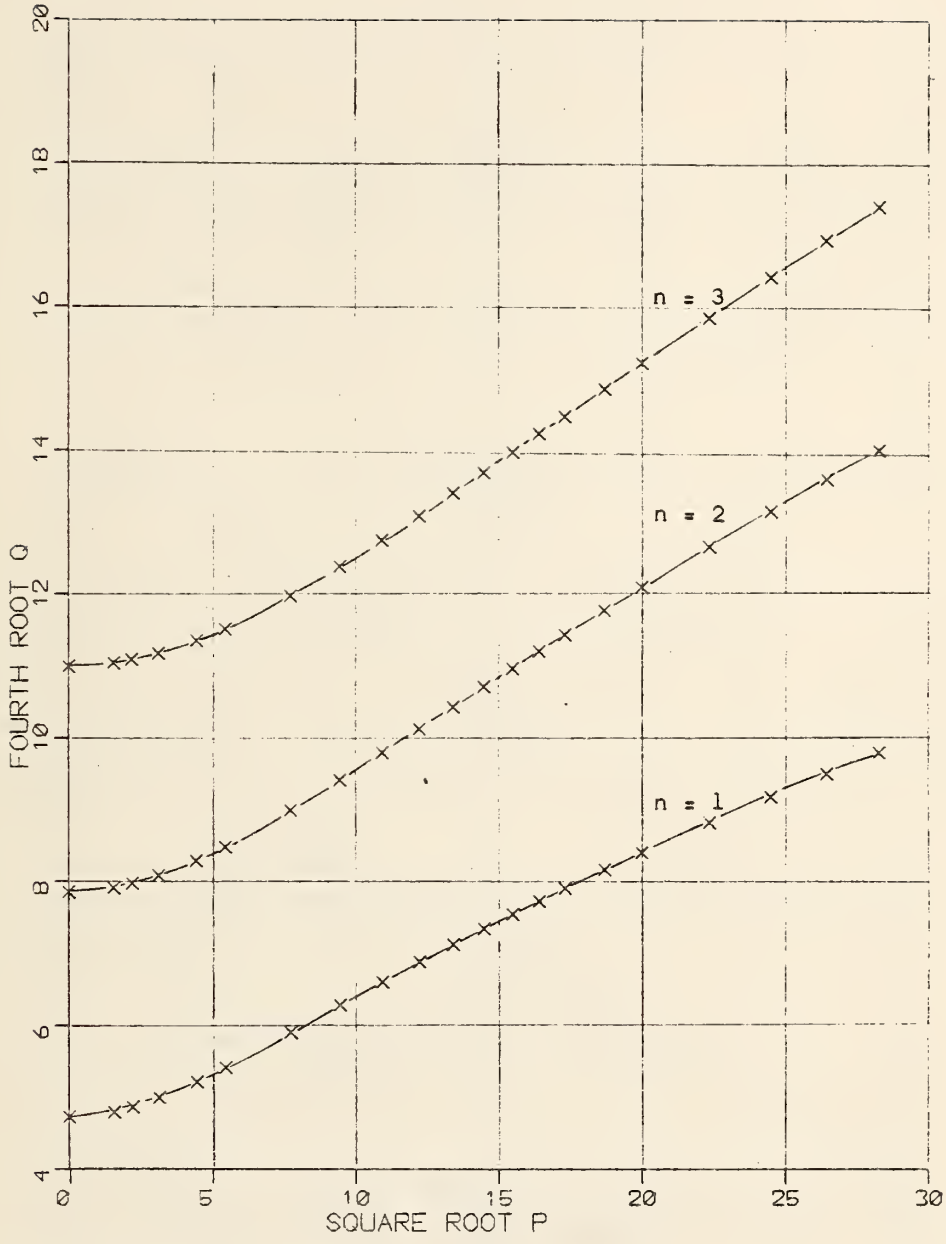
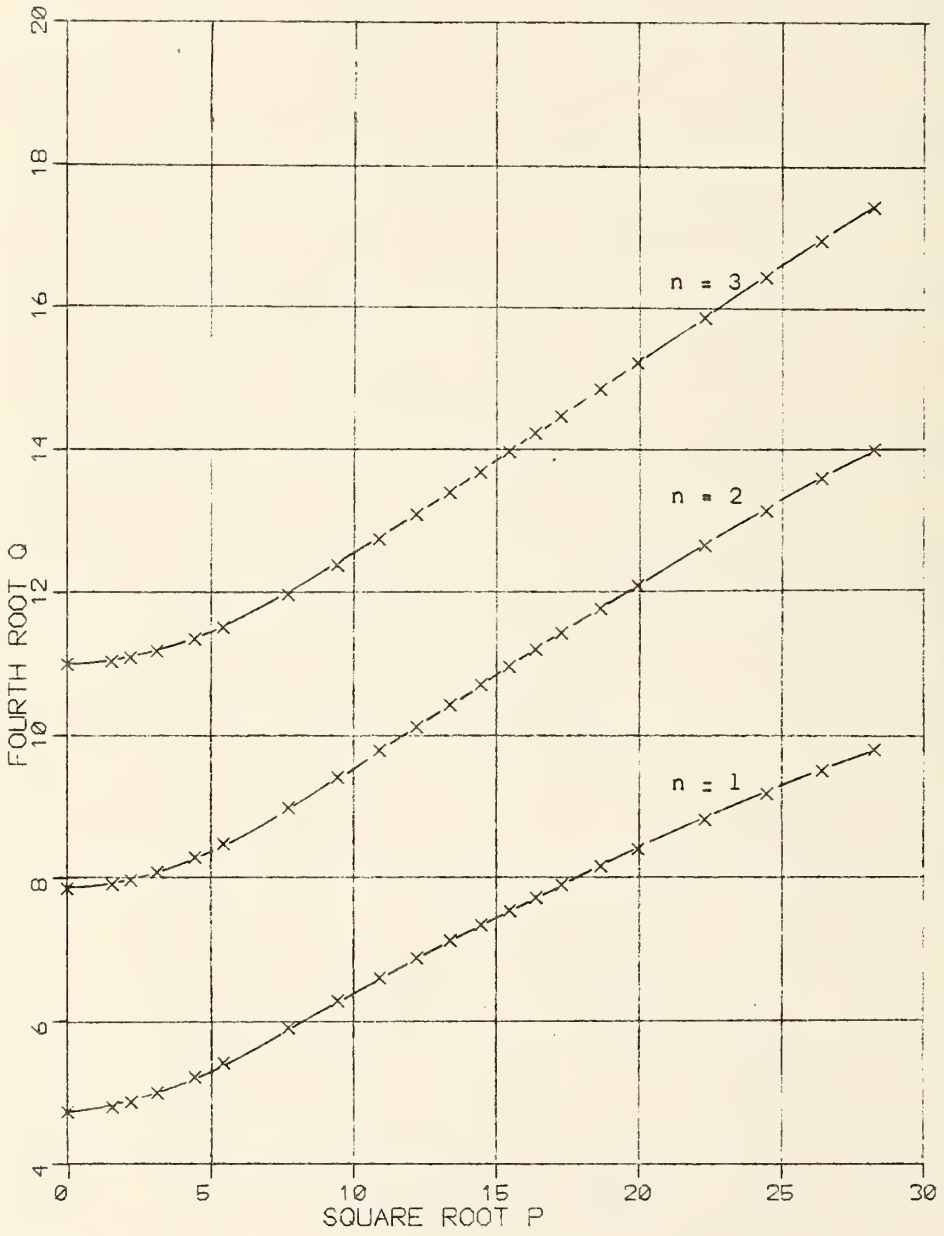


Fig. 77 $\sigma_1 = \sigma_2 = 10{,}000$



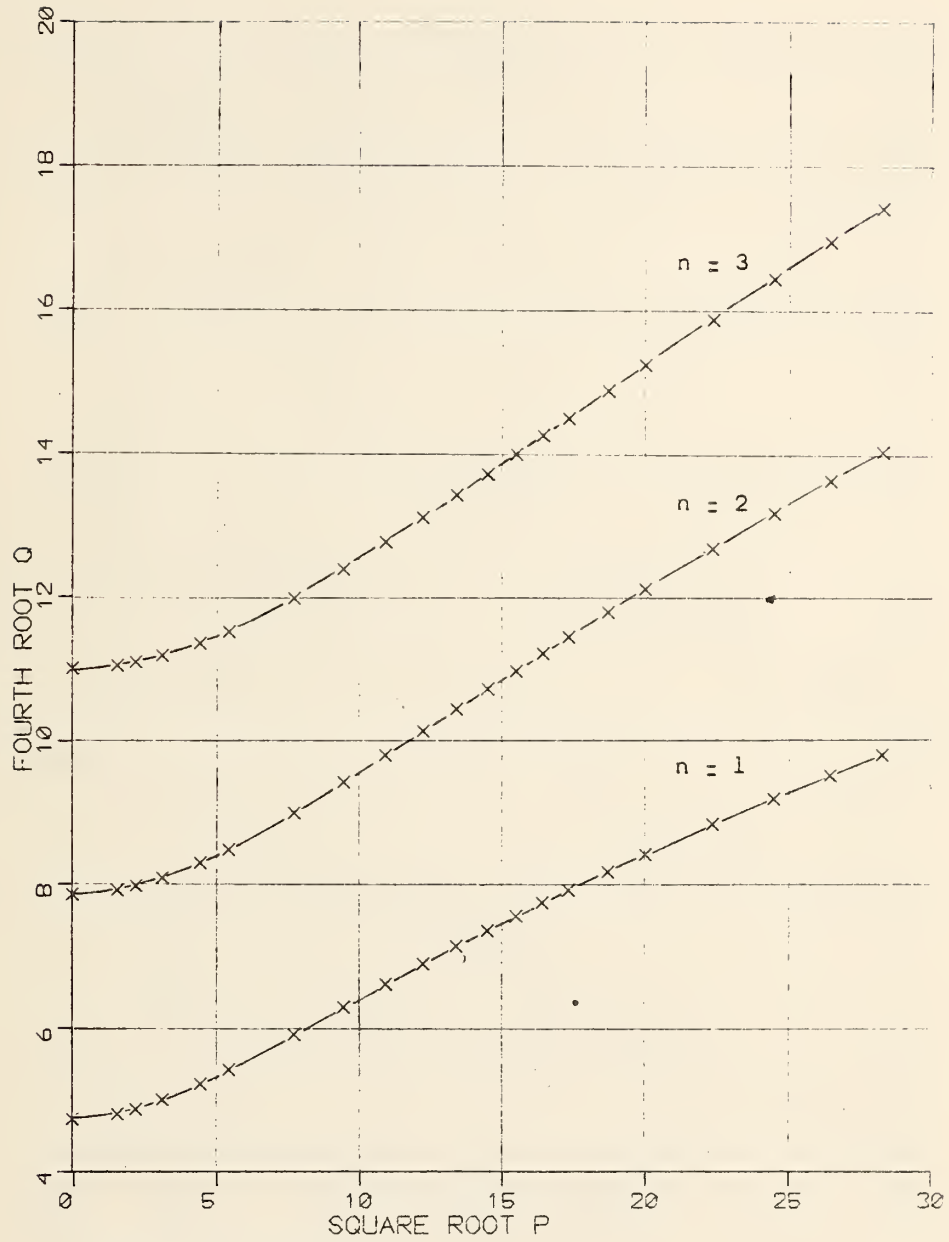
MODE OF VIBRATION = n

Fig. 78 $\sigma_1 = 100{,}000$, $\sigma_2 = 20{,}000$



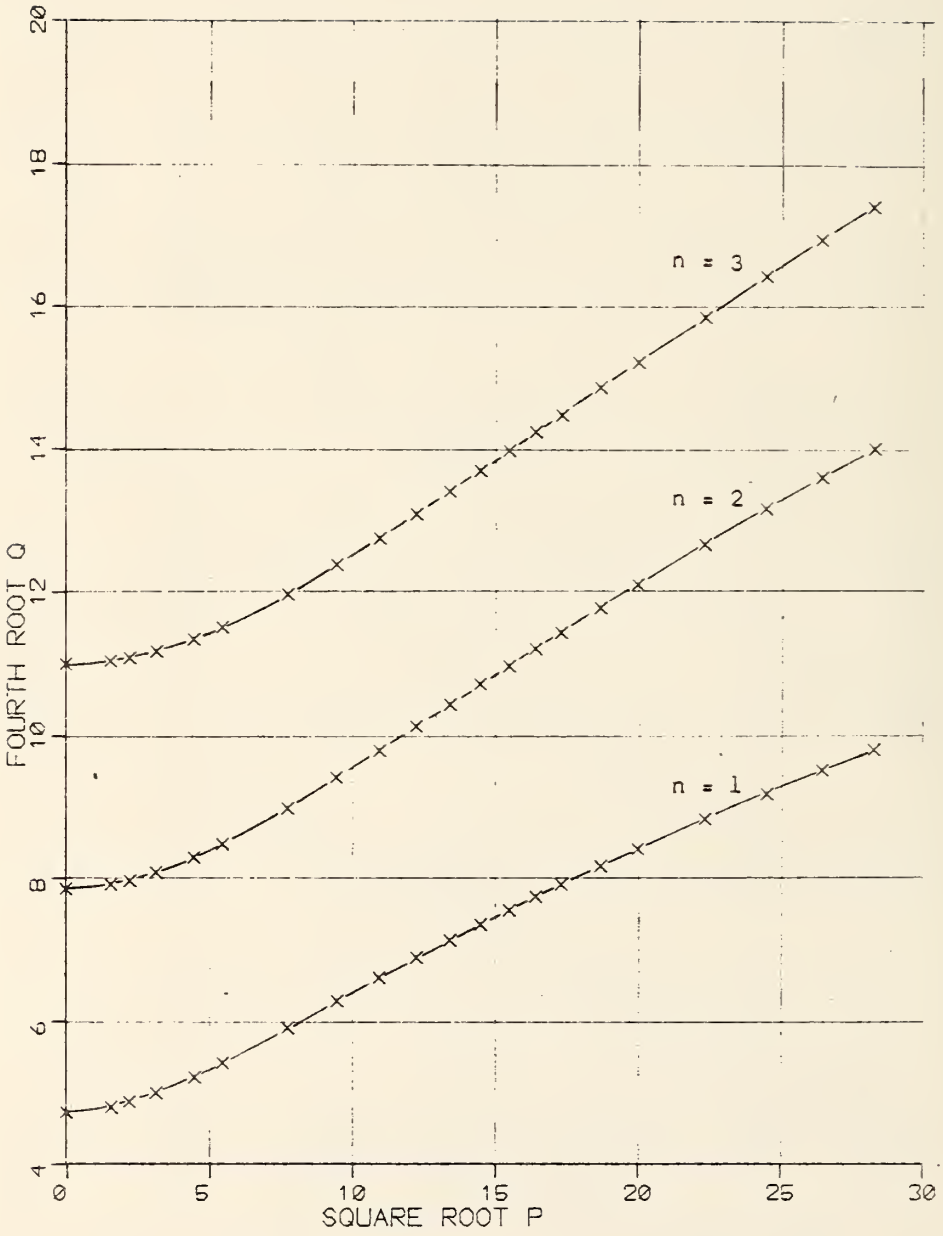
MODE OF VIBRATION = n

Fig. 79 σ_1= 100,000 ,σ_2= 40,000



MODE OF VIBRATION = n

Fig. 80 σ_1= 100,000, σ_2= 60,000



MODE OF VIBRATION = n

Fig. 81 σ_1= 100,000, σ_2= 80,000

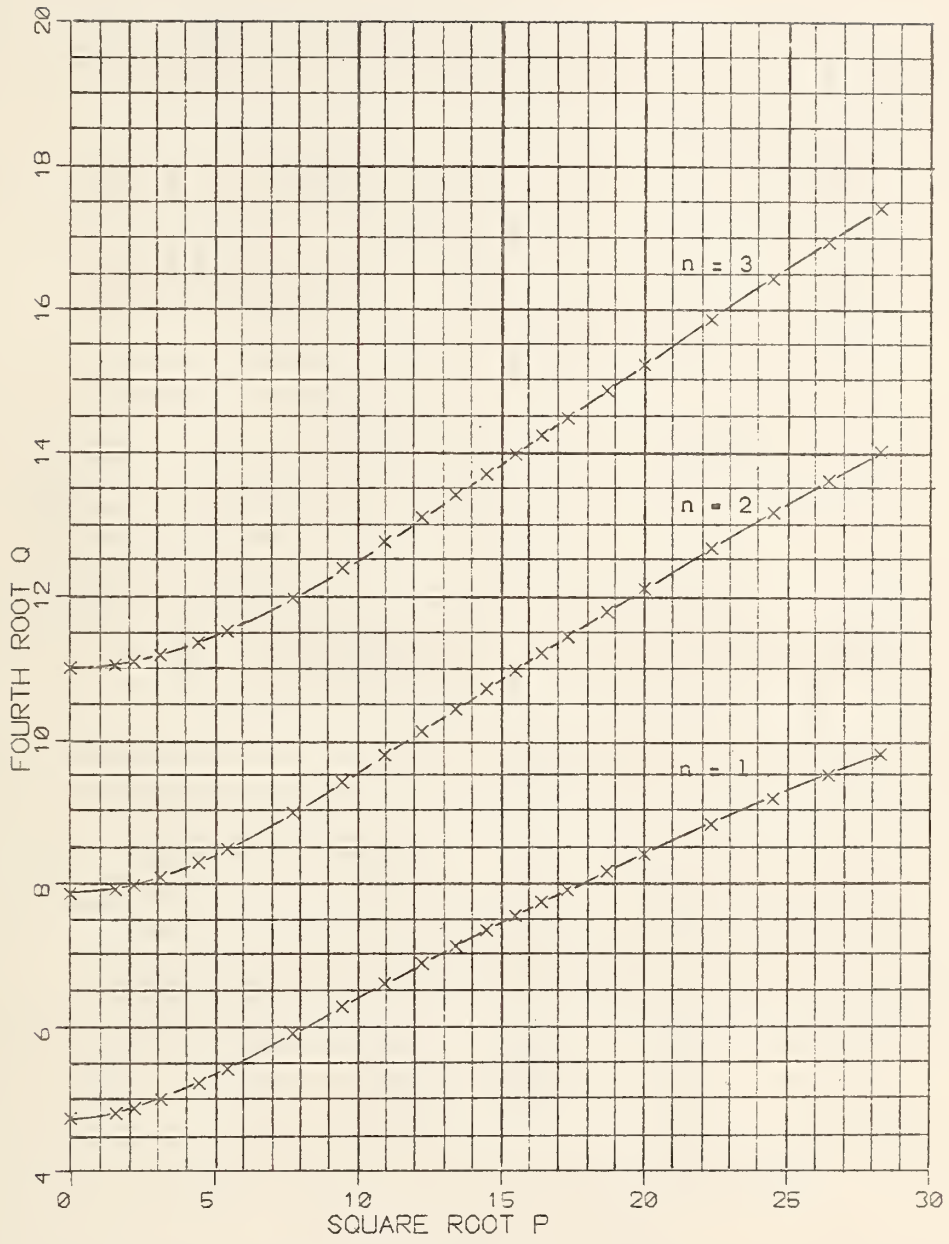
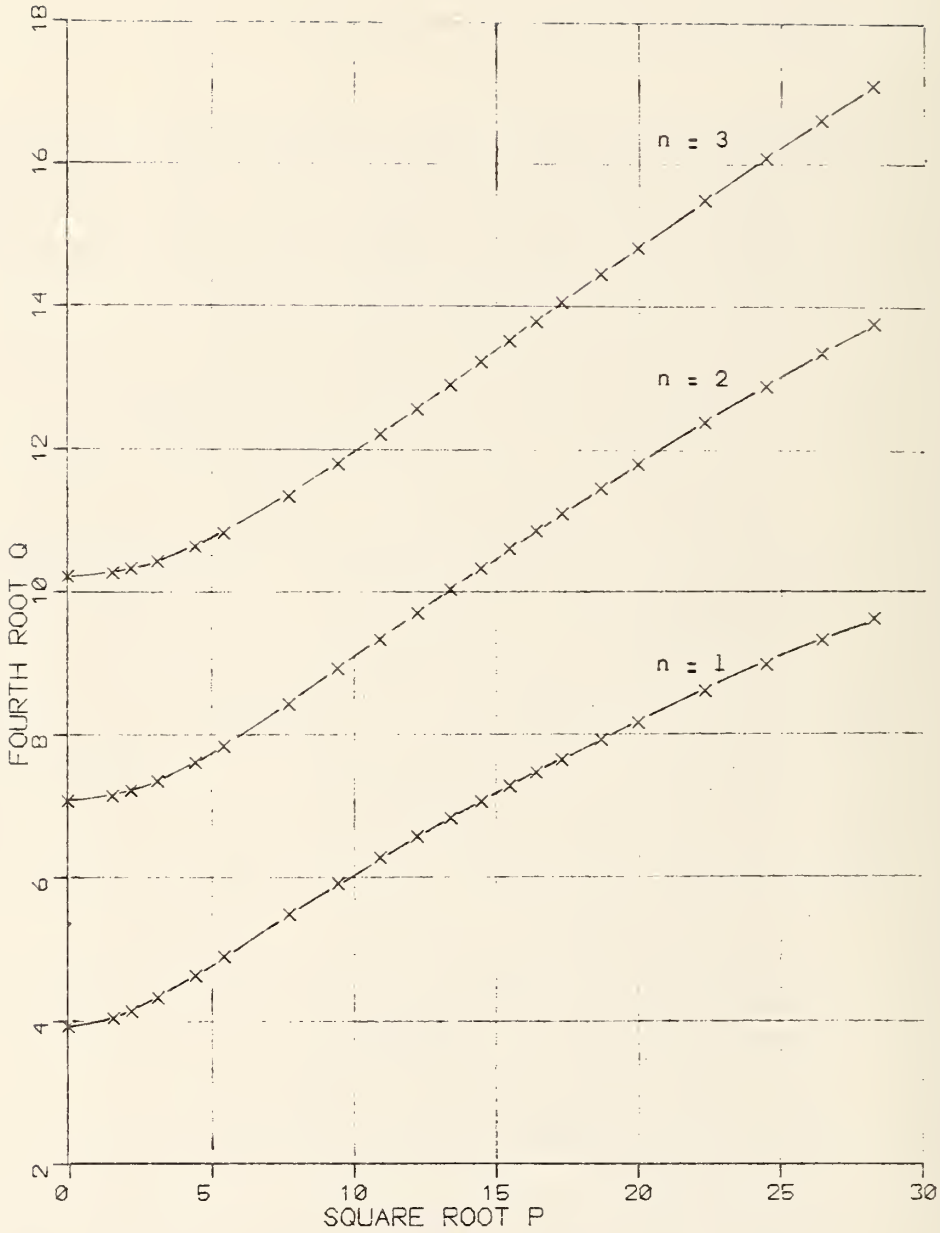


Fig. 82 $\sigma_1=\sigma_2$ = 100,000



MODE OF VIBRATION = n

Fig.83 Frequency Graph, one end hinged, other end fixed

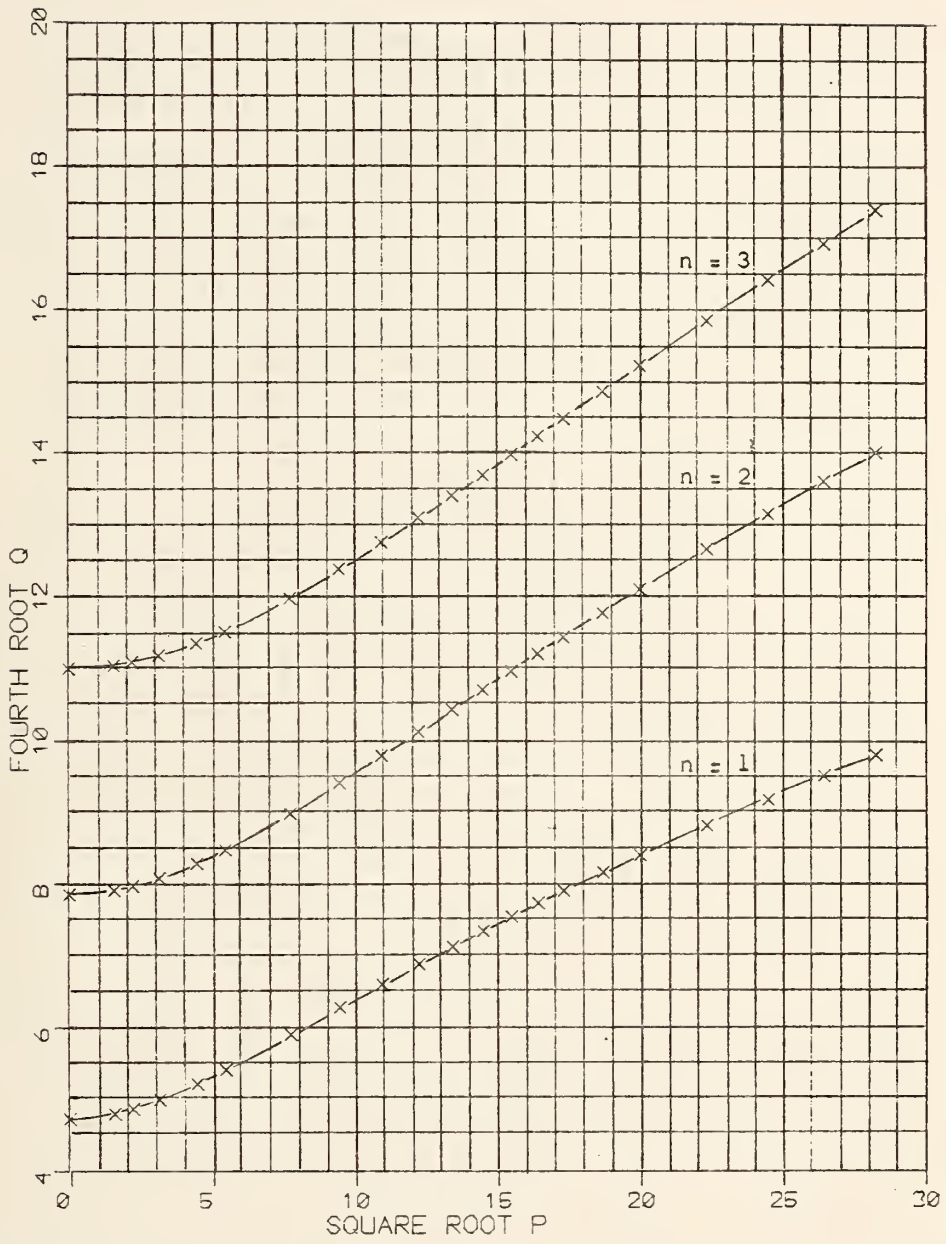


Fig. 84 Both ends fixed

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